

# BNL superconducting RF guns—technology challenges as ERL sources

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## Abstract

The design, fabrication and commissioning of a 703.75 MHz SRF photoinjector with a retractable multi-alkali photocathode designed to deliver 0.5 A average current at 100% duty factor is the present undertaking of the electron cooling group in the Collider Accelerator Division of Brookhaven National Labs. This photoinjector represents the state of the art in photoinjector technology, orders of magnitude beyond the presently available technology, and should be commissioned by 2007. The R&D effort presently underway, and the focus of this paper, will address the numerous technological challenges that must be met for this project to succeed. These include the novel physics design of the cavity, the challenges of inserting and operating a multi-alkali photocathode in the photoinjector at these high average currents, and the design and installation of a laser system capable of delivering the required 10 s of watts of laser power needed to make this photoinjector operational.

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## 1. Introduction

The use of an SRF photoinjector for the BNL high average current, 0.5 A, energy recovery linac (ERL) hinges on the successful design of a half cell 703.75 MHz photoinjector powered by two opposed 500 kW fundamental power couplers designed to deliver up to 0.5 A average current at 100% duty factor. The photoinjector will deliver 2 MeV electrons at 352 MHz which will be subsequently accelerated to 20 MeV through a novel 5 cell SRF Linac, [1] make a single pass around the ring and be

decelerated through the Linac back to 2 MeV and then be ejected from the ring.

The generation of 0.5 A photoelectrons at 100% duty factor places serious demands on all aspects of the photoinjector, including the physics design, the photocathode material choice and insertion device, the associated laser system, and the engineering of a power coupler to deliver 500 kW under continuous operation. Furthermore, the ERL needs to operate in a number of different modes aimed at demonstrating different parameters and capabilities of the photoinjector, injection optics and overall ERL performance. These modes are 352 MHz, 0.5 A, 1.4 nC/bunch to demonstrate 0.5 A average current, 9.38 MHz, 0.2 A, 20 nC/bunch for applications in cooling of the heavy

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ion collider RHIC, as well as in a single pulse start-up mode for diagnostics, alignment and commissioning. It is the goal of this paper to give an overview of how the design of this photoinjector is proceeding, as well as to address the numerous technological challenges presented by such an endeavor.

## 2. Photoinjector design

This injector is being designed as the first high average current, SRF gun with a CsK<sub>2</sub>Sb demountable photocathode capable of being inserted and retracted while maintaining the vacuum integrity and cleanliness of the photoinjector. A schematic of the photoinjector and associated helium vessel and cryostat is shown in Fig. 1. This initial geometry of the photoinjector was based on the 5 cell SRF linac structure that has already been designed and is nearing the end of its assembly phase [2]. One of the major benefits of the 5 cell design is that it allows for all higher-order modes (HOM) to pass out of the resonant structure to a ferrite absorber in the warm section thus greatly reducing the cryogenic load, an obvious necessity at these high currents.

After several design iterations, the latest gun geometry has evolved significantly from the original design. These changes are both to the overall shape of the resonant structure as well as to the beampipe diameter. In the original design the beampipe flared to 19 cm to allow for propagation of the HOMs. It was found that the beampipe diameter could be kept at 10 cm, the same dimension as the iris of the cavity and still adequately propagate the HOMs. One of the key benefits of having a reduced beampipe geometry is that it greatly simplifies the coupling of the 1 MW RF power to the beam, as well as significantly

reduces the size of the gate valve needed at the end of the beampipe, a tremendous weight and cost savings. A schematic of the new geometry can be seen in Fig. 2.

Additionally, a focusing solenoid, constructed from a high temperature superconductor, will be inserted just inside the gate valve in order to help decrease the beam emittance. This will be much easier with the reduced beampipe size as it will significantly reduce the amount of material needed to make the solenoid, significantly reducing the power needed to drive the solenoid and subsequently the heat generated during its operation.

## 3. CsK<sub>2</sub>Sb photocathode

The second component to the high average current photoinjector is the multi-alkali photocathode. As described above, there is a provision for inserting an independently cooled, electrically isolated photocathode into the photoinjector as seen in Fig. 1. The cathode insertion device is a complicated arrangement that must satisfy a number of different criteria. It must be electrically and thermally isolated from the cavity in order to avoid additional heat loads to the cryogenic system due to the fact that the cathode is maintained at an elevated temperature relative to the cavity and because of the high average current being extracted from the photocathode. It must also be designed such that when inserted there is a means of avoiding multipactoring or other RF losses through the insertion mechanism. This is being addressed using a newly designed quarter wave choke joint shown in Fig. 3. The quarter wave choke joint is much easier to fabricate than the alternative proven design, presently used by Rossendorf, which incorporates a more complex arrangement including an additional, detuned cavity [3].

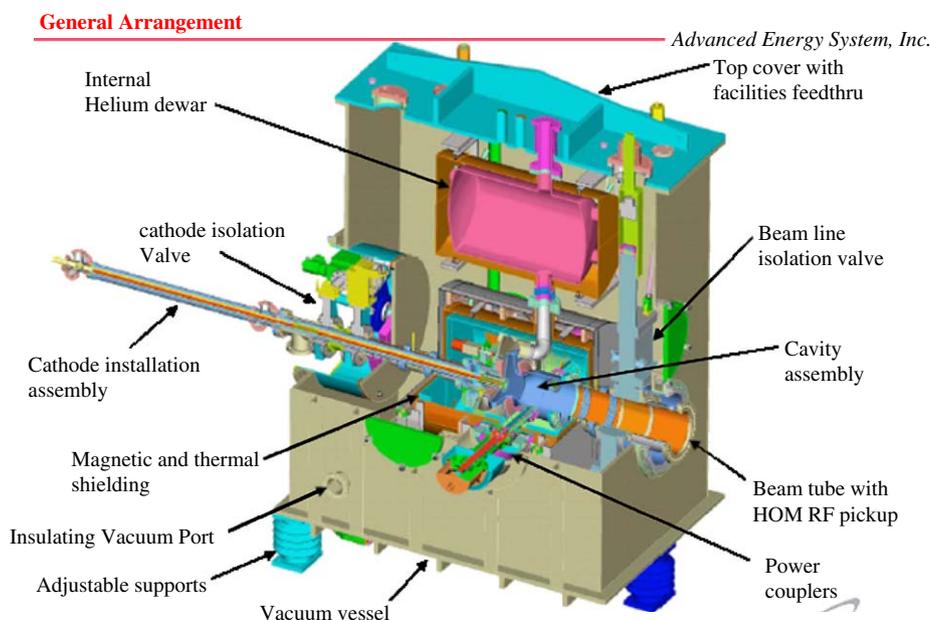


Fig. 1. The general arrangement for the 703.75 MHz photoinjector inside of the helium vessel and cryostat in which it will be housed with the retractable photocathode inserted from the left.

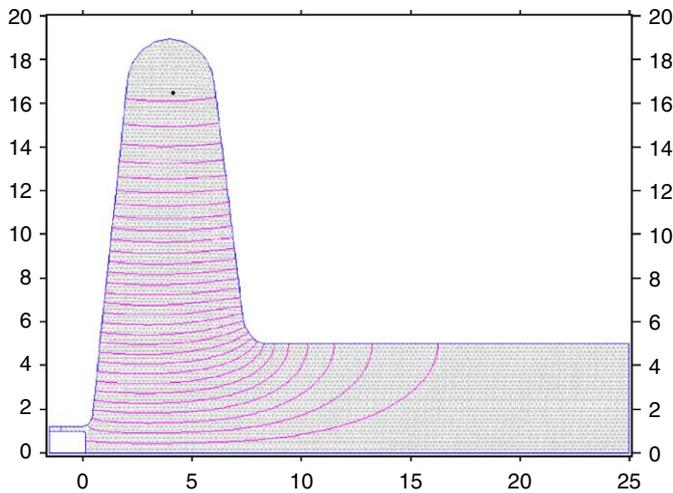


Fig. 2. The layout of the SRF photoinjector inside the helium vessel and cryostat with the gate valve shown in the hashed section, the solenoid would lie between the gate valve and gun.

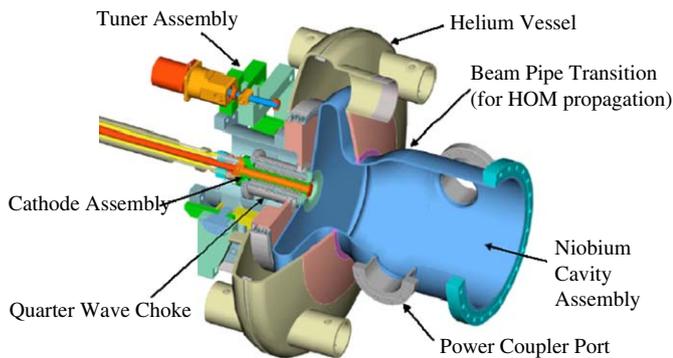


Fig. 3. The quarter wave RF choke joint that is being designed for the SRF photoinjector is shown along with a more detailed view of the photoinjector itself.

The quarter wave choke joint concept has undergone preliminary testing and will be subsequently tested using a fully SRF 1.3 GHz photoinjector presently in place at BNL [4].

The photocathode material of choice for this project is  $\text{CsK}_2\text{Sb}$ , and was selected based on its high quantum efficiency and convenient operational wavelengths. (QE of 2–14% at 532 nm and 10–30% at 355 nm) The fabrication of the photocathode is a process that is highly dependent on the exact deposition system configuration, thus making it difficult to directly import a recipe from another source. The general technique, obtained through our collaboration with David Dowell at SLAC, formerly at Boeing, is to deposit  $\sim 200 \text{ \AA}$  of antimony followed by the deposition of  $\sim 150 \text{ \AA}$  of potassium and then deposition of cesium while monitoring the QE. The cesium deposition is terminated when the QE reaches a maximum. Further research is underway to optimize the process using an alternating deposition technique whereby after the initial deposition the cathode is exposed to water vapor or oxygen, then cesium is re-deposited while monitoring the QE. This cycle

continues back and forth until the QE no longer increases with the addition of Cs, but has been shown to result in a 5 fold increase in QE at 532 nm [5].

The technological challenges presented by using a  $\text{CsK}_2\text{Sb}$  photocathode in a SRF photoinjector revolve around the vacuum conditions to which the photocathode is exposed. The multi-alkali photocathodes all require extremely good vacuum conditions,  $10^{-10}$  Torr or better, in order to maintain their designed QE for a reasonable length of time. This has been demonstrated at BNL to be over 2 months for  $\text{CsK}_2\text{Sb}$  photocathodes stored in  $2 \times 10^{-10}$  Torr vacuum. Previous use of multi-alkali photocathodes in a normal conducting gun has resulted in photocathode lifetimes of only a few hours due to the degradation of the vacuum once the gun was made operational. The reason for the degradation in the normal conducting gun is due to the fact that most of the RF power is dissipated into the walls of the cavity, resulting in heating of the cavity, and subsequent outgassing of species such as  $\text{CO}_2$  or water vapor that poison or reduce the QE of the photocathodes. This should not be a problem in an SRF photoinjector as it is maintained at 2 K and the power should all be coupled to the beam.

An associated challenge that must be overcome is the complex interface between the cathode preparation system and photoinjector itself. Due to the complex arrangement for the cooling of the photocathode stalk the photocathode deposition must be done in a specially designed chamber that will accommodate the cathode insert. As such the photocathode fabrication will take place in a separate UHV vessel. This necessitates the use of a load-lock and transport system to move the prepared cathode to the photoinjector. This is a complicated arrangement as the transfer must all be done under UHV conditions not exposing the cathode to any possible contamination. As seen in Fig. 4, the backside of the photoinjector vacuum vessel is fitted with two gate valves and a small intermediate chamber. During the exchange process the cathode must be brought to this intermediate chamber, attached and then evacuated and baked prior to opening the valve from the transporter arm. The photocathode must then be inserted

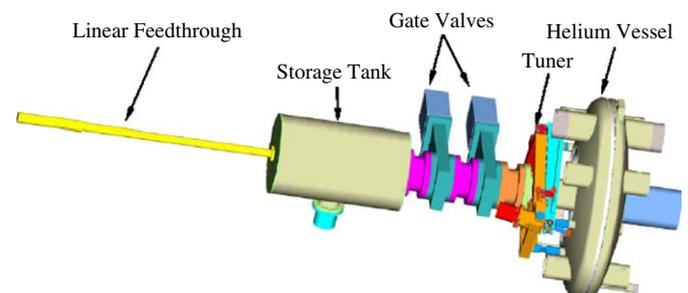


Fig. 4. The rear portion of the photoinjector vacuum vessel and the photocathode transport arm are shown to identify the load-lock section required to maintain the vacuum integrity of the photoinjector and transport, a critical item for the sensitive multi-alkali photocathodes.

Table 1

The laser system needed in order to generate 0.5 A average current at either 532 or 355 nm is listed here taking into consideration the possible use of a secondary emitter amplifier with a modest secondary emission yield of 50 (SEY)

Laser wavelength (nm)	CsK <sub>2</sub> Sb QE (%)	SEY	Desired current (A)	Laser power to cathode (W)
532	3	0	0.5	38
532	<b>3</b>	<b>50</b>	<b>0.5</b>	<b>0.7</b>
355	9	0	0.5	17
355	<b>9</b>	<b>50</b>	<b>0.5</b>	<b>0.35</b>

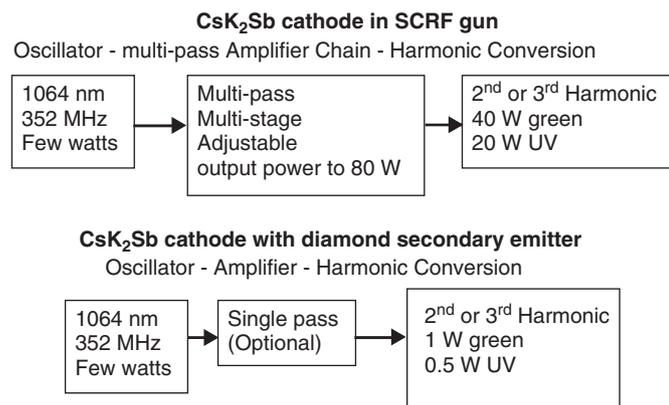


Fig. 5. This is a presentation of two possible laser system layouts depending on the outcome and implementation of the secondary emitter research.

approximately 1 m into the photoinjector and positioned at the exact location for operation.

Once the cathode is in place for operation, the temperature of the photocathode must be reduced to avoid depositing an unnecessary heat load into the cryostat. The operation of the CsK<sub>2</sub>Sb photocathode has recently been tested down to 170 K and has seen only a 10% decrease in QE [6]. This gives us confidence that it will be possible to operate the photocathode at LN<sub>2</sub> temperatures thus relaxing the heat load on the helium system.

A final effect that is presently being investigated is the possible contamination of the photoinjector by the photocathode material. It is possible that the cesium could migrate from the photocathode to the gun walls and lead to possible location for field emission. This risk is being assessed in our photocathode preparation chamber where a high power laser is focused onto the photocathode to produce electron current densities comparable to those required for the SRF photoinjector operation. This should confirm whether there is a need to be concerned with cesium migration into the photoinjector.

A final possible addition to the photocathode system that would alleviate all of the above-mentioned vacuum and migration issues is the possible use of a diamond secondary emitter capsule. This would serve two purposes,

first to increase the electron yield from the photocathode by 200–400% [7], and second it would serve as a capsule window behind which the photocathode material would be protected from the photoinjector environment. Once a secondary emitter capsule can be constructed it will revolutionize the photoinjector and greatly reduce the demands on both the photocathode material and the associated laser system.

#### 4. Laser system

The final challenge associated with our high average current photoinjector is the laser system needed to generate the 0.5 Amp average current. This laser system could take a number of different configurations depending on both the desired wavelength of operation and the use of a secondary emitter. Ignoring the secondary emitter at this time, the laser needs to operate at either the second or third harmonic of the Vandate laser (532 or 355 nm). The laser power needed to generate the 0.5 A average current is shown in Table 1 and can be arrived at by using a master oscillator followed by an amplifier chain as shown in Fig. 5. The exact method could take one of several possible configurations, each having its own merits. The 352 MHz repetition frequency would most likely require the use of several oscillators/amplifiers at 50–100 MHz synchronized by a master clock. This has the major benefit that if one oscillator/amplifier segment fails it is still possible to operate with the remaining units. A more detailed description of optimal laser systems can be found was presented in this workshop [8].

#### 5. Conclusion

A vigorous R&D effort is underway at BNL in collaboration with Advanced Energy Systems and several other national labs to develop the first SRF photoinjector designed for the next generation, ampere class, high average current ERLs. Significant progress is being made on all necessary research fronts and this should culminate in the successful operation of the BNL ERL in late 2007. This project is the key to future FEL and ERL-based light sources and should open a new era for small research FEL with tremendous potential at a fraction of the present day costs.

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## References

- [1] I. Ben-Zvi, et al., In Proceeding of PAC 2005, Knoxville, TN, 2005.
- [2] R. Calaga, et al., In Proceeding of EPAC 2004, Lucerne, Switzerland, 2004.
- [3] D. Janssen, et al., In Proceeding of ERL 2005 Workshop, Newport News, VA, 2005.
- [4] T. Rao, et al., In Proceeding of PAC 2005, Knoxville, TN, 2005.
- [5] Private communication with David Dowell of SLAC.
- [6] A. Burrill, et al., In Proceeding of PAC 2005, Knoxville, TN, 2005.
- [7] X. Chang, et al., In Proceeding of PAC 2005, Knoxville, TN, 2005.
- [8] M. Shinn, et al., Talk presented at ERL 2005 Workshop, Newport News, VA, 2005, [http://conferences.jlab.org/ERL/2005/talks/WG1/WG1\\_Shinn\\_Tue\\_0830.pdf](http://conferences.jlab.org/ERL/2005/talks/WG1/WG1_Shinn_Tue_0830.pdf).