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R&D ERL: SRF Electron Gun

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INTRODUCTION

When the BNL high current ERL was first envisioned the choice of injector went through several iterations before concluding that an SRF injector was the appropriate choice for the task at hand. The design requirements were quite stringent as the injector had to be designed to reach currents never before achieved in any injector. The overall goal was to design an injector capable of delivering up to 0.5 Ampere at 703.75 MHz. This criteria was set based on the need to demonstrate high average current energy recovery at the ERL so that future machines could be designed and built with confidence in the injector. For the ERL the injector needs to be capable of accelerating electrons to 2-2.5 MeV with charges ranging from 0.7 to 5 nC per bunch depending on the operational parameters being studied. These criteria led to a ½ cell photoinjector designed to accommodate a demountable photocathode utilizing a novel quarter wave choke joint for the cathode insertion mechanism. The cavity requires a total of 1 MW of power coupled to the beam in order to meet the high current application, necessitating two 500 kW RF power couplers. This AP note will review the overall physics design and analysis, the fabrication sequence, and the testing plan for this cavity.

PHYSICS

The physics design of the cavity went through several iterations as the various operating parameters were identified and the cavity geometry and associated beam dynamics were examined. The reader is referred to Rama Calaga's Thesis for a more in depth discussion of the design of this cavity [1], but the general parameters are given in table 1, with a model of the cavity shown in figure 1. The key items that needed to be addressed were, 1) achieving the desired accelerating gradient in the ½ cell structure while optimizing the cathode face position and spot size, 2) ensuring that the 1 MW of RF power required could be delivered to the cavity without adversely affecting the beam quality, 3) designing a cathode insertion mechanism, and RF choke design that could handle the power required from both the RF as well as the laser system for a cathode designed to deliver 0.5 ampere, and 4) installation of a suitable solenoid in close proximity to the cavity to ensure the beam emittance was contained within the operating regime necessary for the ERL to work as designed.

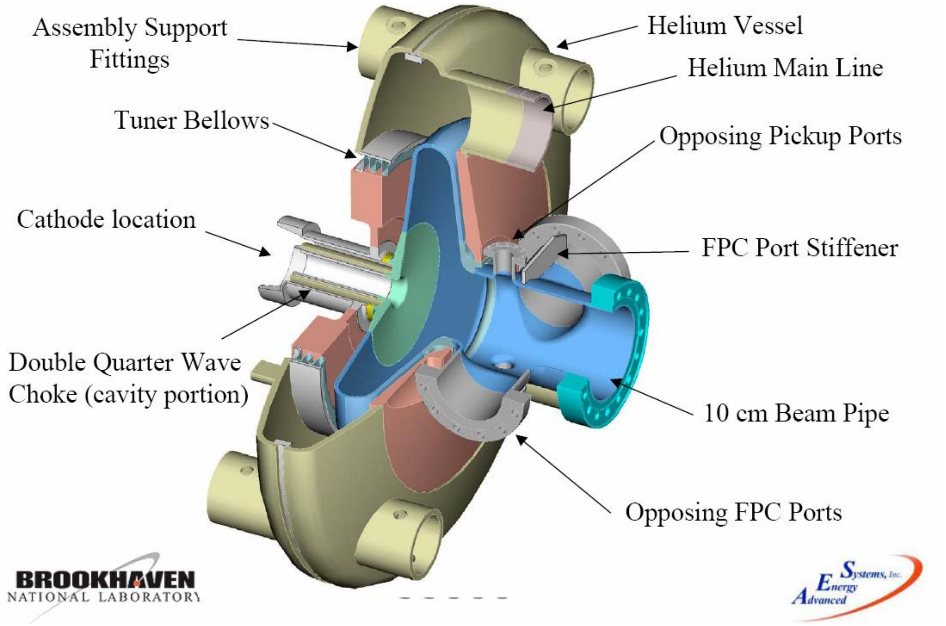

Figure 1. The ½ cell SRF injector designed for use in the ERL shown with its helium vessel and identifying all of the major components of the cavity

These items were all addressed through several different mechanisms. First the cavity design was thoroughly vetted through an iterative process between the physicist, using Microwave Studio®, Superfish and Parmela, and the engineering group utilizing Ansys®, to ensure the cavity design would be suitable for the ERL. One of the key features that required extensive analysis was the FPC and the shape of the tip of the antenna. After several iterations it was decided to use an antenna tip that matched the radius of the beampipe of the injector. This "pringle" tip is shown in figure 2, and provides a very nice way to achieve the desired Q external of the FPC (3e4) while not penetrating the beampipe as one would have to do with a standard antenna. The other cavity feature that required extensive analysis was the double quarter wavelength choke joint used to allow for insertion of a demountable, thermally isolated cathode stalk. The details of the choke joint analysis can be found in reference 2 [2], but the basic concept is the provide a method of isolating the normal conducting cathode from the SRF cavity, while being able to dissipate the current that results from operating at high average RF power without quenching the cavity. Details of the photocathode and cathode insertion device can be found in reference 3. [3]

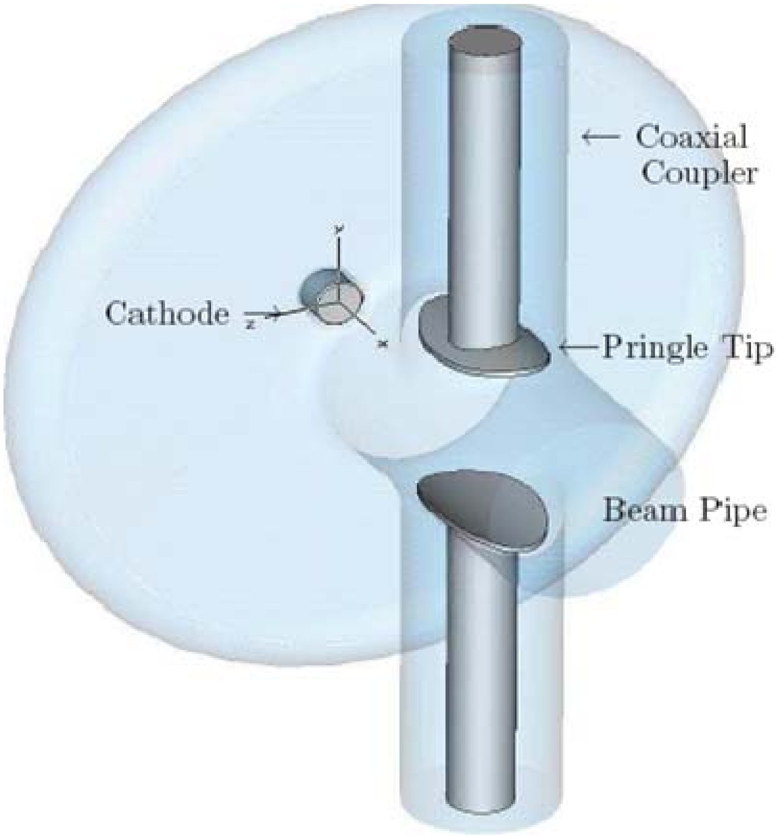

Figure 2. The pringle tip of the fundamental power couplers shown matching the beampipe radius to help reduce the impact of the FPC on the electron beam.

One of the items that had to be addresses as the cavity design was being finalized was the multipacting analysis for both the cavity as well as the choke joint geometry. The two components were studied independently and both analyses showed favorable results. In order to ensure multipacting is suppressed in the choke joint two added precautions were taken. First the choke joint surface was prepared with anti-multipacting triangular grooves to help break up the resonance condition that contributes to multipacting. Second, the cathode stalk has the ability to be modified to be biased with a DC voltage to help suppress multipacting, and/or pass through the multipacting barrier, should one arise.

Table 1. A list of pertinent Physics parameters for the SRF injector.

Parameter	Units	Value
Frequency	MHz	703.75
Iris radius	cm	5
Equator Diameter	cm	37.9
Cavity length	cm	25
Beam kinetic energy	MeV	2
Peak electric field	MV/m	35.7
Peak magnetic field	A/m	58740 (73mT)
Stored energy	Joule	8.37
QRs (geometry factor)	Ω	3.52
R/Q	Ω	96
Qe (external Q)		37000
Power input	MW	1
Maximum current	mA	500
Emittance at 1.4 nC	μm rms normalized	1.4
Cathode recess	mm	1
Cathode spot size	mm diameter	5
Emission phase	Degrees	25
Longitudinal loss factor	V/pC	0.7
Transverse loss factor	V/pC/m	32

The final key item is the high temperature superconducting solenoid that is being placed at the end of the cavity to help focus the electron beam on it's way to the accelerating cavity. This solenoid has been designed and built by Ramesh Gupta and the Superconducting Magnet Division at BNL and has already undergone its acceptance testing. The solenoid is design to provide a field of 0.014 Tesla while keeping the stray fields that reach the cavity to below 10 mGauss. This has been accomplished by using a bucking coil adjacent to the primary coil, and by moving the magnetic shielding in between the solenoid and the cavity. A detailed description of both the solenoid design and the simulation data can be found in reference 4. [4]

As the cavity design matured, the higher order mode (HOM) analysis began. The HOM analysis for this cavity was carried out using ABCI and later microwave studio. The total HOM power dissipated by a 500 mA, 1.4 nC beam was calculated to be ~0.5 kW. [5] Figure 3 shows a plot of the monopole and dipole modes in the cavity along with a spectrum of the harmonics of the injector. The two different plots shown were from the original analysis of the cavity beampipe radius, and for this cavity the 5 cm beampipe radius spectrum is the one under consideration. [5] Due to the frequency of the injector the harmonics spectrum is fairly sparse and spread out and avoids overlapping with any HOMs.

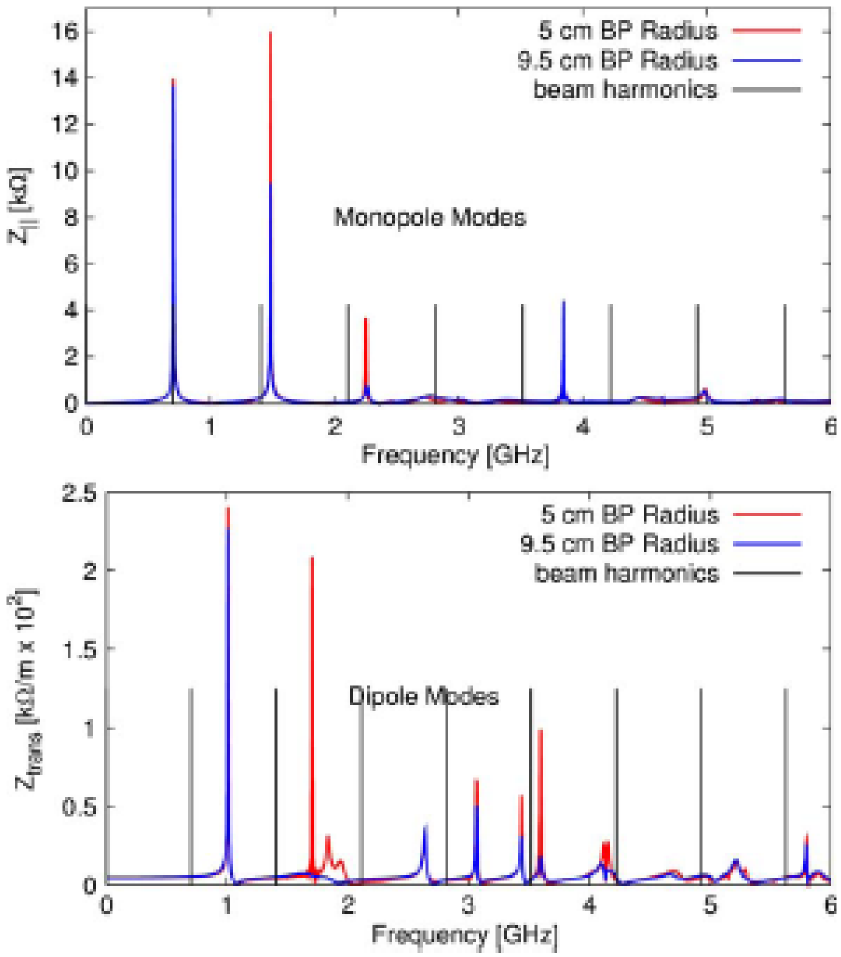

Figure 3. The impedance spectrum calculated using ABCI for the monopole and dipole modes for two different radius beampipes. The beam harmonics are shown in black.

MECHANICAL DESIGN

Once the cavity physics design was complete the processing of coming up with an appropriate mechanical design of the cavity, helium vessel and cryomodule began. This was the first cavity built at BNL that was subjected to the ASME pressure vessel code, and as such introduced several unforeseen delays. In the end the cavity and helium vessel, parts of which define the pressure boundary, were designed, fabricated and tested as required by the code. Figure 4 shows the complete cryomodule design for the cavity. The key features of the cryomodule are the aforementioned cavity, 500 kW FPCs, the HTS solenoid and the cathode insertion mechanics. The other obvious feature shown in figure 4 is the ballast tank above the cavity. This is designed to provide a helium reservoir for operations as the ERL does not include a 2K refrigeration plant. For operation the cavity and ballast tank are filled at 4K, and then the vapor space is pumped down to 23 Torr for 2 K operation. The ballast tank can be refilled sub-atmospheric; however the operation will likely have to stop for this process to occur. Regardless, the system is designed to provide 3-4 hours of operation between refills depending on the dynamic heat load applied.

The cavity was fabricated utilizing both RRR-300 Nb sheet as well as ingot material. This was necessary as the back surface of the cavity and the base of the choke joint region needed to be machined from one piece to ease the welding and fabrication processes, as well as to produce a cavity that could be built and inspected as required by the ASME code. The helium vessel for the cavity is titanium, which is then surrounded by multi-layer super-insulation and then two layers of mu-metal magnetic shielding. This is followed by a liquid nitrogen shield and then the space frame which supports all of the aforementioned structures. The ballast tank will then be installed over the cavity, insulated and then lowered into the rectangular vacuum vessel.

CAVITY TESTING AND CRYOMODULE INTEGRATION

The cavity fabrication was completed in early December 2009, and the cavity has now been tuned and being readied for cleaning, vertical RF testing, and assembly into a hermetic string. This process will begin at Jefferson Laboratory, similar to the 5 cell accelerating cavity used in the ERL. The cavity will undergo a bulk buffer chemical polishing (BCP) treatment, followed by a furnace treatment at 600°C, and then a light BCP and high pressure rinse (HPR) prior to being tested.

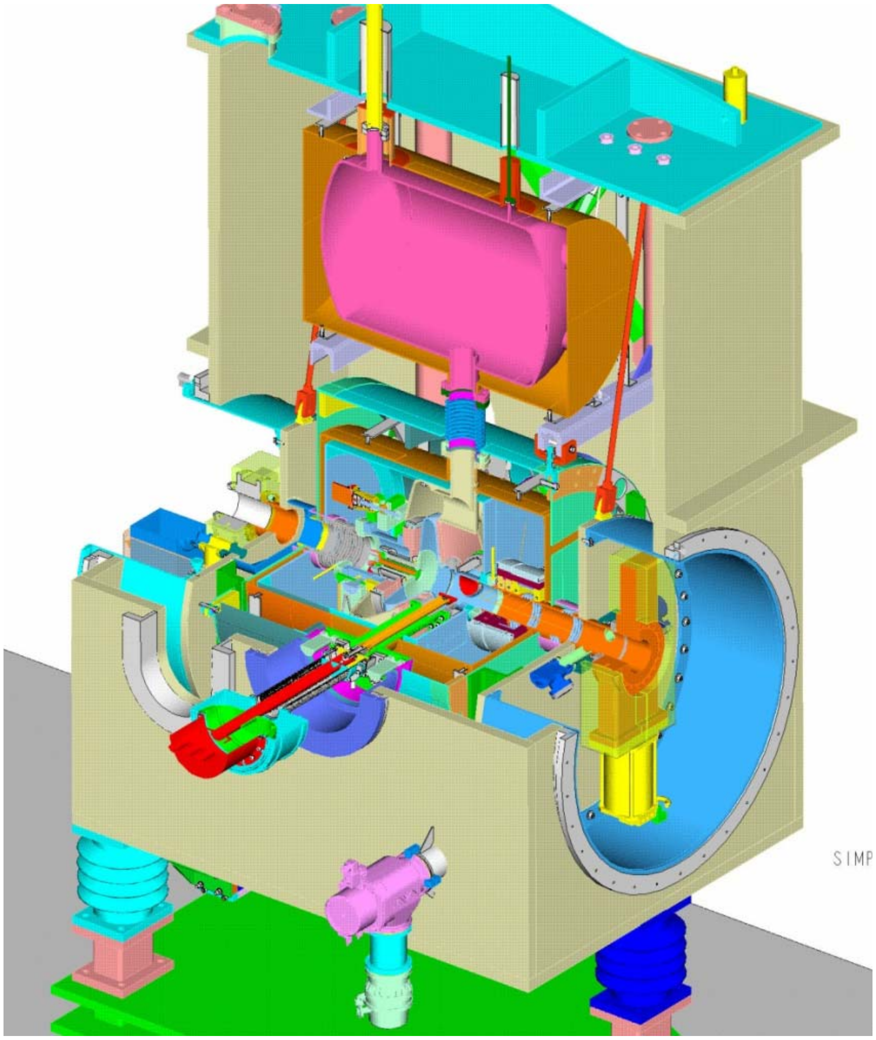

Figure 4. The cryomodule for the SRF injector for the ERL.

The HPR being utilized for this cavity has been built at BNL and successfully used on the 5 cell cavity. The reason for its re-use is based on the need to HPR the choke joint region, and the tight tolerances that present themselves for this operation. The BNL HPR can be modified and made rigid enough to ensure the HPR wand tracks normal to the turntable and does not collide with the choke joint, or any other part of the cavity. This is of critical importance as any strike of the cavity could render it useless.

Following successful initial VTA testing of the cavity, a mock cathode will be inserted and tested to verify the cavity performance with the cathode stalk, as well as the evaluate the possibility of multipacting in the choke region. Should multipacting occur the VTA cathode is designed to be biased with a DC voltage that should allow us suppress the multipacting and carry out a test of the cavity. After these tests the helium vessel will be welded onto the cavity and it will be tested once again prior to integration into the hermetic string assembly, shown in figure 5.

The hermetic string assembly will include the cavity and helium vessel, the tuner mechanism, the HTS solenoid as well as two large steel plates that are part of the vacuum vessel boundary, the instrumentation trees and the gate valves at either end of the cavity. This assembly will be built on the rail system shown in figure 5 which will also serve as the shipping fixture and the rails onto which the balance of the cryomodule will be built.

Once the cavity arrives back at BNL the cryomodule construction should take approximately 3 months, at which time the cavity will be moved to the ERL cavity for preliminary testing.

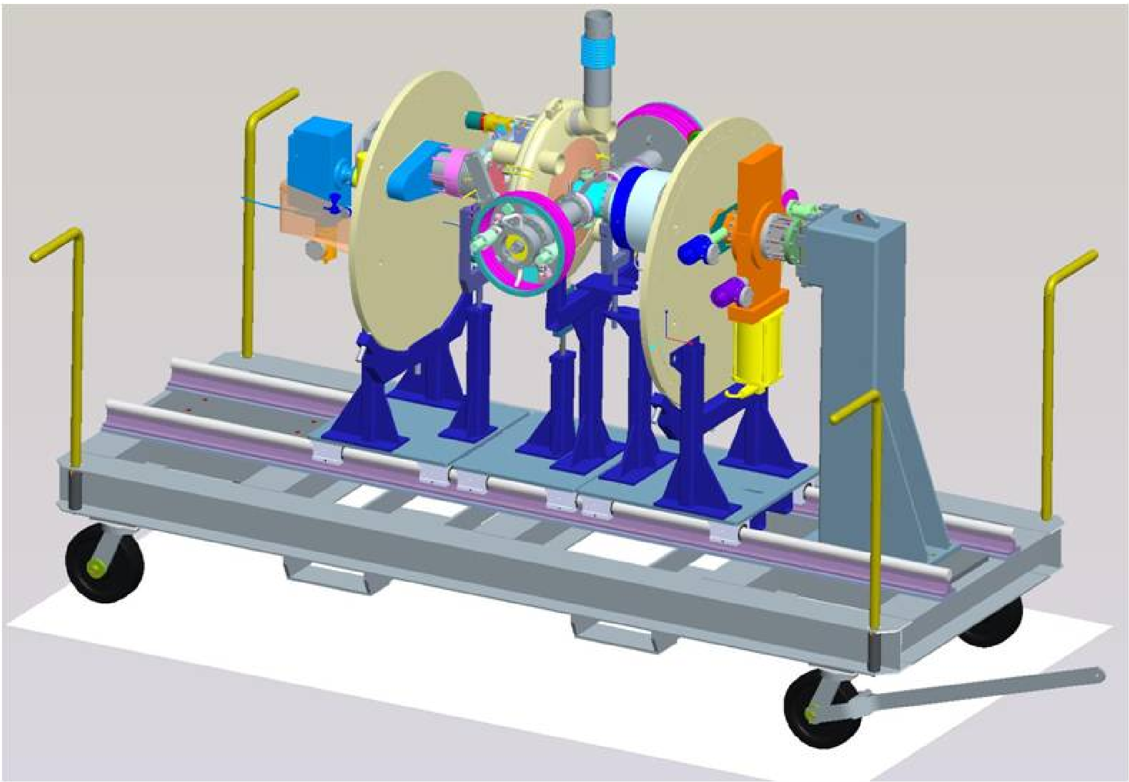

Figure 5. The SRF injector hermetic string assembly mounted on the assembly/shipping rail system.

CONCLUSION

A novel SRF injector has been proposed and fabricated for use in the high current ERL test facility. The cavity will use a novel photocathode insertion mechanism and double quarter wave choke joint to allow for the insertion of a normal conducting photocathode into the SRF injector. In addition this gun will utilize two 500 kW RF power couplers, designed for c.w. operation to provide 1 MW of RF power to the cavity in order to drive up to a 0.5 ampere beam. Finally the cavity will utilize a high temperature superconducting solenoid in close proximity to the cavity, thus requiring careful design and testing prior to its insertion into the cryomodule. The first testing of the cavity should take place in early 2010 with first beam in early 2011.

REFERENCES

[1] R. Calaga, "Linac Beam Dynamics & Ampere Class Superconducting RF Cavities at RHIC," Stony Brook University 2006, http://www.agsrhichome.bnl.gov/People/rcalaga/thesis.html

[2] V. Nguyen-Tuong, L. Phillips and J. Preble for Tunnel Dust, Inc., *priv. comm.*

[3] D. Pate, "R&D ERL-Photocathode Deposition and Transport System", C-AD AP Note.

[4] http://www.bnl.gov/magnets/staff/gupta/Talks/erl-hts-solenoid/hts-solenoid-gupta-ko-021407.pdf

[5] R. Calaga, I. Ben-zvi, X. Chang, D. Kayran, V. Litvinenko, "High current SRF gun at 703.75 MHz", Physica C, **441** (2006), 159-72.