SLAC-PUB-9382

Investigation of the Stability of the RF Gun of the SSRL Injector System

Jessica N. Moore

Office of Science, Energy Research Undergraduate Laboratory Fellowship

Loyola Marymount University

Stanford Linear Accelerator Center

Palo Alto, California

August 14,2002

Prepared in partial fulfillment of the requirements of the Office of Science, DOE Energy Research Undergraduate Laboratory Fellowship under the direction of Benjamin Scott in Stanford Synchrotron Radiation Laboratory (SSRL) at Stanford Linear Accelerator Center.

Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

Work supported in part by the Department of Energy contract DE-AC03-76SF00515.

Table of Contents

Abstract

Investigation of the Stability of the RF Gun of the SSRL Injector System. **JESSICA** N. MOORE (Loyola Marymount University, Los Angeles, **CA** 90045) BENJAMIN SCOTT (Stanford Linear Accelerator Center, Palo Alto, **CA** 94309).

In the previous three years, Stanford Synchrotron Radiation Laboratory (SSRL) has experienced electron beam instabilities in the injector system of the Stanford Positron Electron Asymmetric Ring **(SPEAR).** Currently, for approximately the past four months the radio frequency (RF) *gun* of the linear accelerator injector system of the **SPEAR** at SSRL has become increasingly unstable. The current of the RF gun has become progressively sluggish and the lifetime of the cathode Within the RF *gun* has been much shorter than expected. The cathode also sustains many unexplained damages. The instability of the RF gun affects the entire operation of SPEAR, creating substantial inconvenience. **Through** mechanical, design, and procedural analysis of the RF *gun* and the cathode that emits the electron beam of the linear accelerator, **a** solution to prolong the life of the cathode and secure the stability of the gun **can** be found. The thorough analysis **of** the ***gun*** and cathode involves investigation into the history of cathode installation and removal through the years of SPEAR operation **as** well **as** interviews with SSRL personnel involved with the upkeep of the gun and cathode. From speaking with SSRL employees and reviewing several articles many possible causes for beam instability were presented. The most likely cause of the SSRL gun instability is excessive back bombardment that can be attributed to **running** the cathode at too **high** a temperature.

Introduction

Background

SSRL (Stanford Synchrotron Radiation Laboratory) was established in 1973 as Stanford Synchrotron Radiation Project (SSRP). From 1973 to 1979 Stanford Synchrotron Radiation Project's synchrotron radiation source, SPEAR (Stanford Positron Electron Asymmetric Ring), was dedicated to High Energy Physics (HEP) experiments, with SSRP running in parasitic mode. After 1979, SSRP focused mainly on synchrotron research until 1990 when it evolved into Stanford Synchrotron Radiation Laboratory (SSRL). Ever since, SSRL has been purely a synchrotron light source. SPEAR is a circular accelerator that increases the speed of a charged particle, either an electron or positron, to a relativistic velocity (Park, 2000, p.1). The purpose of SPEAR is to cause electrons to emit synchrotron radiation (SR), also known as electromagnetic radiation which is emitted when an electron travels in a curved path (Winick, 1994). This is made possible by keeping the particles accelerating near the speed of light; at every curved section of the path, the particles emit synchrotron radiation. The most intense radiation is extruded from the electrons using bending magnets, wigglers, and undulators (Winick). The particles are directed around SPEAR by the dipole magnets, also known as bending magnets, which cause radiation to be emitted (Winick). Wigglers and undulators are magnets whose fields cause the particles to move in wave-like motion to either increase the intensity of the radiation emitted or to broaden the electromagnetic spectral of the electrons so they can reach a higher x-ray energy (Mcdunn & Quinn, ¶ 1). A wiggler is an insertion device with successive poles, in a wiggler the SR of each individual electron is added incoherently so that the total radiation power is proportional to the radiation of a single particle ($\propto n_e$). This is known as incoherent synchrotron radiation. An undulator, on the other hand, produces coherent synchrotron radiation.

An undulator causes the electrons to be in phase at a given pole causing the radiation amplitudes to be additive; this results in a total radiation power proportional to the square of the number of electrons ($\propto n_e^2$) (Winick). An undulator then intensifies the radiation by the inverse amount the wavelength has been decreased (Winick). At each trough and crest the particle emits radiation and energy; therefore, SSRL acquires the majority of energy and radiation out of every supply of particles. Synchrotron radiation of electrons can be useful in other areas of expertise, such as the medical field and the semiconductor industry. Synchrotron radiation provides information about the arrangement of atoms in biological and chemical materials which is useful in the making of an x-ray microscope. Also, SR has the ability to identify the electronic structure of materials and surfaces making it possible to develop new materials for faster, better computer chips (Mcdunn & Quinn, ¶ 2).

For the functioning of SPEAR other systems are required. These are the injector system, the Booster, and the BTS (Booster to SPEAR) system. The injector system, also known as the Linac (linear accelerator), is equipped with a radio frequency (RF) gun, the source of the electron beam, and a thermionic cathode. The Linac also contains quadrupoles to focus the beam of electrons, dipoles that direct the path of the electrons, and a chopper that selects particular electron bunches of the beam. The linear accelerator increases the energy of the beam from 2.0 MeV starting at the gun to 120 MeV as the beam progresses through the Linac to Booster (LTB) path (refer to Figure 1). The Linac directs the beam of electrons to the Booster system, which directs the electrons in a circular path to cause the particles to emit synchrotron radiation and also to increase the energy of the beam to 2.3 GeV through acceleration (Park, 2000, p.1). The Booster system consists of dipole magnets used as deflection magnets, quadrupoles as focusing magnets, and radio frequency cavities that increase the energy of the beam. The beam then goes through the BTS system to the SPEAR where it reaches its final energy of 3 GeV.

Injector System

The particular concentration of this project is the injector system, also known as the Linac, or more specifically, the radio frequency gun and the thermionic cathode within the gun. The cathode is placed on the first wall of the half cell of the 1.5 cell radio frequency gun. The cathode when heated to a temperature of approximately 950°C emits electrons into the radio frequency gun. SSRL typically heats the cathode to a minimum temperature of 1050°C and a maximum of 1140°C (Weaver et al., 2002, p.2). The RF gun has a frequency of 2856.0 MHz (Park). The frequency through the Linac is determined by the volume of the RF cells of the gun. The type of cathode that is at use in the SSRL at present is Semicon 2, also known as an AET Type #4 cathode, a model from Semicon Associates (Figure 3). The vendor of the RF gun is Advanced Electronic Technologies Associates, Inc (Weaver et al., 2002, p.3). The cathode and radio frequency gun are the basis of which the Linac and the other systems are run. To comprehend this project, the evolution of the beam through the injector system must be known. To wholly recognize the importance of the radio frequency gun and cathode one must also understand the mechanics of the Linac.

The RF gun injects approximately three thousand bunches of electrons per microsecond (μs) of pulse, digitally set at 10 Hz, into the Linac at an approximate energy of 2.0 MeV. The beam is then sent through three consecutive quadrupoles that assist in focusing the beam; the beam proceeds to a large bending magnet known as an "alpha" magnet since it bends the beam in an alpha (α) shape as it passes through the container where the magnet is confined (Figure 2). The alpha magnet compresses the beam to a few hundred picoseconds. The beam is then sent through a chopper, a device that interrupts the electric current of the beam allowing particular bunches of electrons to continue through the Linac to the Booster system while the majority of the bunches are discarded (Winick, 1994).

Problem Description

The reliability of the cathode and RF gun are extremely important to the functioning of the injector system, and therefore, all of SPEAR. As of late, SSRL has been experiencing trouble with the stability of the RF gun. The cathode inside the gun has had an increasingly shorter life span, while the RF gun emits a current at a fraction of the obligatory rate. It is not known if the trouble lies with the cathode or the gun itself. Instead of emitting a current at the usual rate of 20 mA per minute, the injector system has emitted a beam as slow as 4 mA per minute. The slow current produced by the injector system is due to an originally slow beam emitted by the RF gun. Also, the cathode of the RF gun has been replaced six times since initial operation of the RF gun in 1990 (Morales et al., 2002, pp.1-2).

Constant replacement of the cathode is an unnecessary nuisance in that it takes time away from the users of SPEAR. The inconsistency of the current of the RF gun inhibits the proper operation of SPEAR as well. By collecting data and investigating the matter at hand, it is hoped that improvements will be made to prevent such instabilities in the future.

Materials and Methods

Before analysis of the stability of the radio frequency gun and the thermionic cathode could begin, research on the workings of the gun and cathode had to be performed. In the act of researching the gun and cathode engineering notes authored by Mike Nalls, Jim Weaver, and Michael Borland, all who at some point worked on the RF gun and cathode, were extremely beneficial. Also, schematics and drawings of parts of the gun and cathode collected by drafting engineer Tom Anzur were provided. A primer on synchrotron radiation by Herman Winick helped to relate all the information supplied by the collected papers. Finally, getting involved in the everyday schedule that is behind the operation of the Linac was valuable, such as attending operations meetings.

After background information on the gun and cathode was solidified, the next task at hand was to find out more about the instability of the electron beam. First, more reading was required. A written analysis of the cathode by metallurgist, Bob Kirby, was quite insightful. The most effective way to obtain information is to directly ask employees immediately involved with the construction and maintenance of the Linac. A sequence of interviews was given, starting with Bob Kirby.

As previously stated, the first interview was with Bob Kirby, whose area of expertise is cathode analysis. Kirby was able to supply information on the condition of previous cathodes when they were taken out of the gun at the end of their life spans and what the symptom of beam instability could imply about the operating state of the current cathode. Also, Kirby suggested causes of the cathode's short life. Eduardo Guerra of SPEAR Operations was next to be interviewed. Guerra was capable of elaborating on the mechanics of the RF gun and the effects of variation of gun body temperature on the beam stability. Harold Morales, Vacuum System manager, gave his opinion on what could cause the cathode's short life. Mike Nalls, who has tested and worked on the gun and cathode since 1996, spoke of recent changes to the gun's operating system. Dave Ernst shared his knowledge on the water system for the radio frequency gun. Ihioma Nzeadibe, a mechanical engineer, shared his findings on an analysis of a similar gun model. Also, John Schmerge, the Gun Test Facility manager, Sam Park, the RF System manager, and Dr. Helmut Wiedemann, the former director of the SPEAR injector synchrotron, answered general questions about the mechanical aspects of the gun and cathode.

To fully appreciate the delicacy of the gun and cathode it was advantageous to become involved in the testing of the new RF gun and the purchasing of the new cathode. Setting up the testing apparatus for the new gun, researching information on the new cathode vendor, and drafting a drawing of the new cathode were the main tasks accomplished in an effort to comprehend the design aspects of the gun and cathode.

Results*

Possible causes of the beam instability were discovered from successive interviews. All collected theories point to the cathode as the source of the instability.

Kirby and Nalls agreed that there could be a problem with the current design of the cathode. This includes possible flaws in the inner components of the cathode along with the surface of the cathode. Mike Nalls indicated that changing the curved surface of the cathode to a flat surface may have impeded the performance, while Kirby proposed that there were originally cracks on the surface of the cathode which would slow emission and could be attributed to the vendor. Bob Kirby also contributed the view that the cathode may be poisoning itself with hydrocarbon

* Appendix B contains interview notes.

groups which would be the result of poor quality control. He presented the possibility that the heater is giving off hydrocarbons or other harmful elements and poisoning the cathode, therefore shortening its lifespan. Nalls mentioned that during the last shutdown that the heat dam of the cathode had to be removed by force which caused the frequency of the gun to change. To force the gun back to the ideal RF frequency the temperature of the gun had to be controlled by heaters and chillers, which may not have been as stable as the previous water system. Nalls suggested that the inconsistency of the gun frequency could affect the stability of the emitted beam. In contrast, Dave Ernst communicated that the new water system of heaters and chillers was incredibly stable with a variation of ±0.1 degrees Celsius. Ernst advocates a design flaw. More specifically, the cathode is strained due to overheating and perhaps the spring or the filament of the cathode shifts due to thermal expansion which is a theory that Eduardo Guerra supported. On the other hand, John Schmerge reported that after removing several cathodes the spring has never showed any damage whatsoever. Schmerge said the most likely cause of damage to the cathode surface and also the cathode's short life is back bombardment. Sam Park agreed with this hypothesis. Harold Morales proposed that there could be a problem with the heat dam material. The material could be giving off too much heat, therefore overheating the cathode. Morales also suggested the number of coils in the spring may need to be adjusted. The number of coils determines how much heat the spring will conduct away, if the turns of the spring are lessened there is less heat conducted away from the cathode. There are currently 18 turns in the spring, at times the maximum was 25 turns. Lastly, Ihioma Nzeadibe compared the SSRL gun to the gun in operation at SUNSHINE (Stanford University short intense electron source), the lab that Dr. Helmut Wiedemann heads on the Stanford University campus. He noted that Dr. Wiedemann turns off the RF voltage and heater voltage after each run allowing the cathode to completely cool. Dr. Wiedemann also pointed this out; the SUNSHINE gun is exactly the same as the SSRL gun except that it is stable. Dr. Wiedemann has recommended investigating the feedback system.

Discussion and Conclusions

After all possible causes of beam instability were presented it was necessary to review recorded interviews and rule out various hypotheses. The first proposal to be examined is that due to the heat the spring of the cathode is shifting or changing in any way due to thermal expansion. John Schmerge has examined several cathodes; none of the springs have shown any sign of warping or other damage. Although there is a possibility that due to thermal expansion the spring could expand and for a time not be in contact with the cathode. This would result in the over heating of the cathode and could most likely cause permanent damage. Another idea that coincides with this is that the heater or heat dam is giving off hydrocarbons as a result of poor quality control, or rather insufficient pump down of the gun. These parts have also been examined and show no damage. Also, Dr. Wiedemann uses the same gun at his lab and it is usually pumped down to 1×10^{-8} Torr or less, this is a good vacuum, but Dr. Wiedemann acknowledges that cathodes are very sensitive to vacuums. The actual measurement for the SSRL gun is approximately 3.3×10^{-11} Torr. Since the system is pumped down to operating standards, there should be no excess hydrocarbons in the system to poison the cathode. Before 1999, the cathode used was manufactured by Varian, the operating standards were the same and there was not a report of such instability. The idea that the short life of the cathode could be attributed to the vendor is also not a possibility. Again, this same cathode is operating in labs such as SUNSHINE and formerly at APS (Advanced Photon Source) at Argonne National Laboratory, without incident.

There is, however, the possibility that the Semicon cathode is inferior to the Varian cathodes, yet it is highly unlikely that the Semicon cathodes are altogether insufficient. Even though the method of cooling the gun body has changed, the temperature and frequency of the gun are still stable; also the water temperature of the current heater/chiller system is incredibly stable. This would imply that the change in cooling method is not responsible for the instability of the beam current. Lastly, the RF voltage and heater voltage could not effect the emission of the cathode. There is not enough power supplied to significantly change the temperature of the cathode or gun body, therefore there should be no change in frequency or emission that has not been manually implemented by a change to the voltage.

The most likely cause of beam instability and the cathode's short lifetime is back bombardment. This is consistent with the findings in the analysis of the cathode's surface by Bob Kirby. Back bombardment of electrons cause the cathode's surface to eventually resemble a dry lake bed. The cracks in Osmium/Ruthenium surface would allow Barium to dispense onto the surface unevenly. This variation over the small surface of the cathode would certainly affect the emission of the cathode. However, the suspicion that operating at too high of a temperature has put a strain on the cathode carried by a number of technicians and engineers has proved correct. The excessive amount of back bombardment taking place is due to an exceptionally high operating temperature; also, over heating causes the cathode's lifetime to be shortened. Reducing back bombardment will lessen the energy deposited on the cathode, and therefore, reduce the emission fluctuations. The slight fluctuations in the current emission produce great changes in the energy of the injector, which are the reported instabilities. To manage the current fluctuations the feedback control system will operate the gun at a new operating point, a lower temperature. This will be implemented by John Schmerge at startup. After the feedback system is modified it should be observed for a span of about two to three days so any instability can be corrected.

Along with the changes to the feedback system, a new cathode from a new vendor, HeatWave Labs, is being purchased. The cathode is still an M-type dispenser cathode with a Tungsten plug and Osmium/Ruthenium surface. The ideal lifetime of the cathode is approximately three years under standard operating conditions. These conditions are an emitting temperature of 1050°C and a current of 16.5A/cm^2, or 24 A/cm^2 with some sacrifice to the lifespan. This cathode will probably not be installed this upcoming run.

Acknowledgements

I extend my thanks to the Department of Energy – Office of Science for the opportunity to participate in the Energy Research Undergraduate Laboratory Fellowship. I express my appreciation to Helen Quinn and Sekazi Mtingwa.

Much gratitude to my mentor, Benjamin Scott, SSRL Manager, and the staff of Stanford Synchrotron Radiation Laboratory at Stanford Linear Accelerator Center in Palo Alto, California. Special thanks to Evelyn Chin, Tom Anzur, and Ann Trautwein.

The research documented in this paper was performed at Stanford Synchrotron Radiation Laboratory, a national scientific user facility sponsored by the United States Department of Energy and located at Stanford Linear Accelerator Center.

References

Mcdunn, R. A. and Quinn, H. (n.d.). Research Using Synchrotron Radiation. Stanford Synchrotron Radiation Laboratory. Retrieved July 26, 2002 from http://www2.slac.stanford.edu/vvc/ssrl/ssrl-research.html

Park, S. (2000). The SPEAR Injector RF Gun and Linac Performance. *International Linac Conference, 20,* 113-115. Retrieved July 1, 2002 from http://accelconf.web.cern.ch/AccelConf/l00/papers/MOB09.pdf

Winick, H. (editor) (1994). Synchrotron Radiation Sources- A Primer. Singapore: World Scientific Publishing Co.

Morales, H., Nalls, M., Park, S., & Weaver, J. (2002, March 13). SSRL Cathode Summary. Stanford Synchrotron Radiation Laboratory.

Weaver, J., Nalls, M., Morales, H. (2002, March 13). Thermionic rf (Trf) Gun Cathodes. Stanford Synchrotron Radiation Laboratory.

Figures

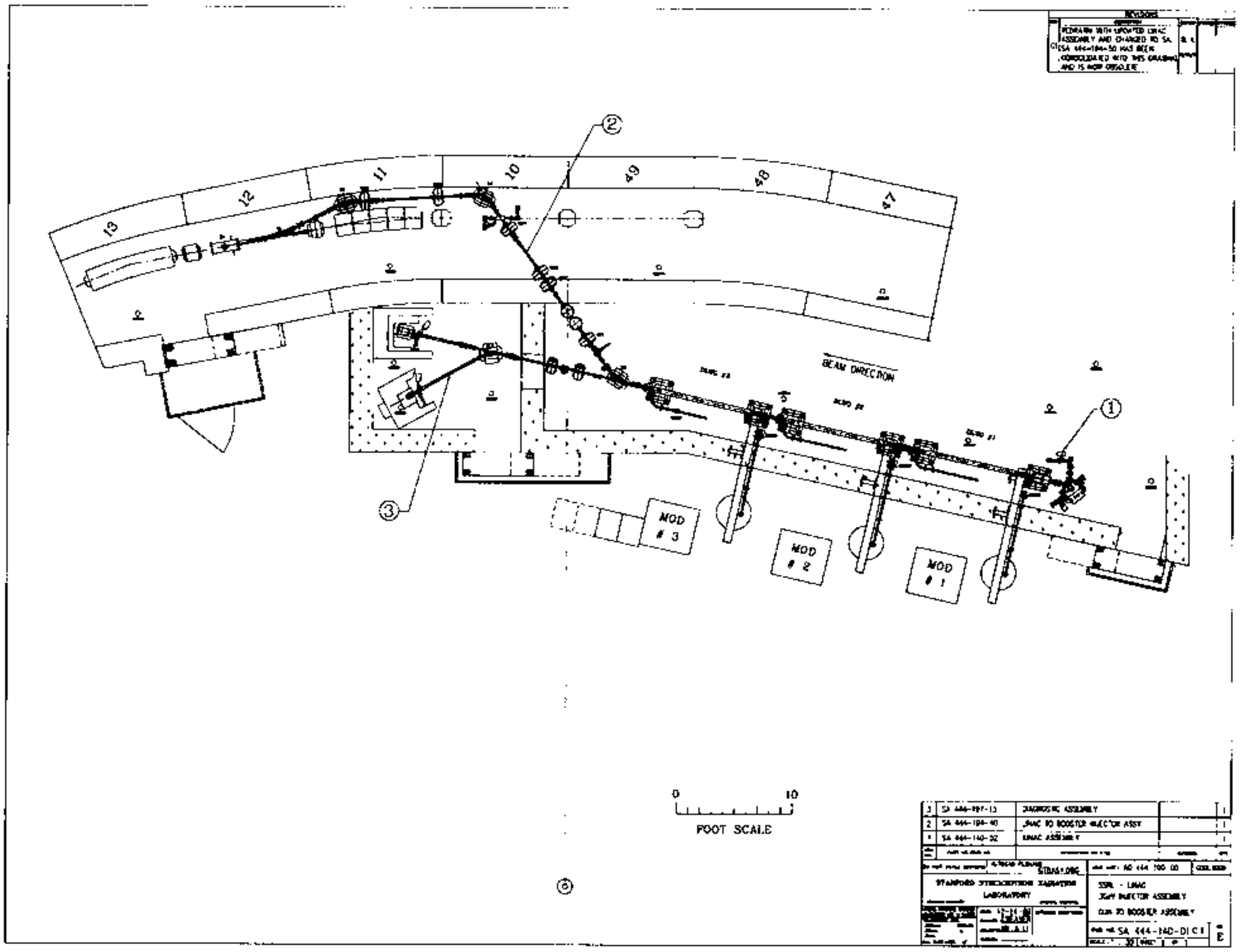

Figure 1. A bird's eye view of the Linac to Booster (LTB) setup from SSRL Autocad drawings.

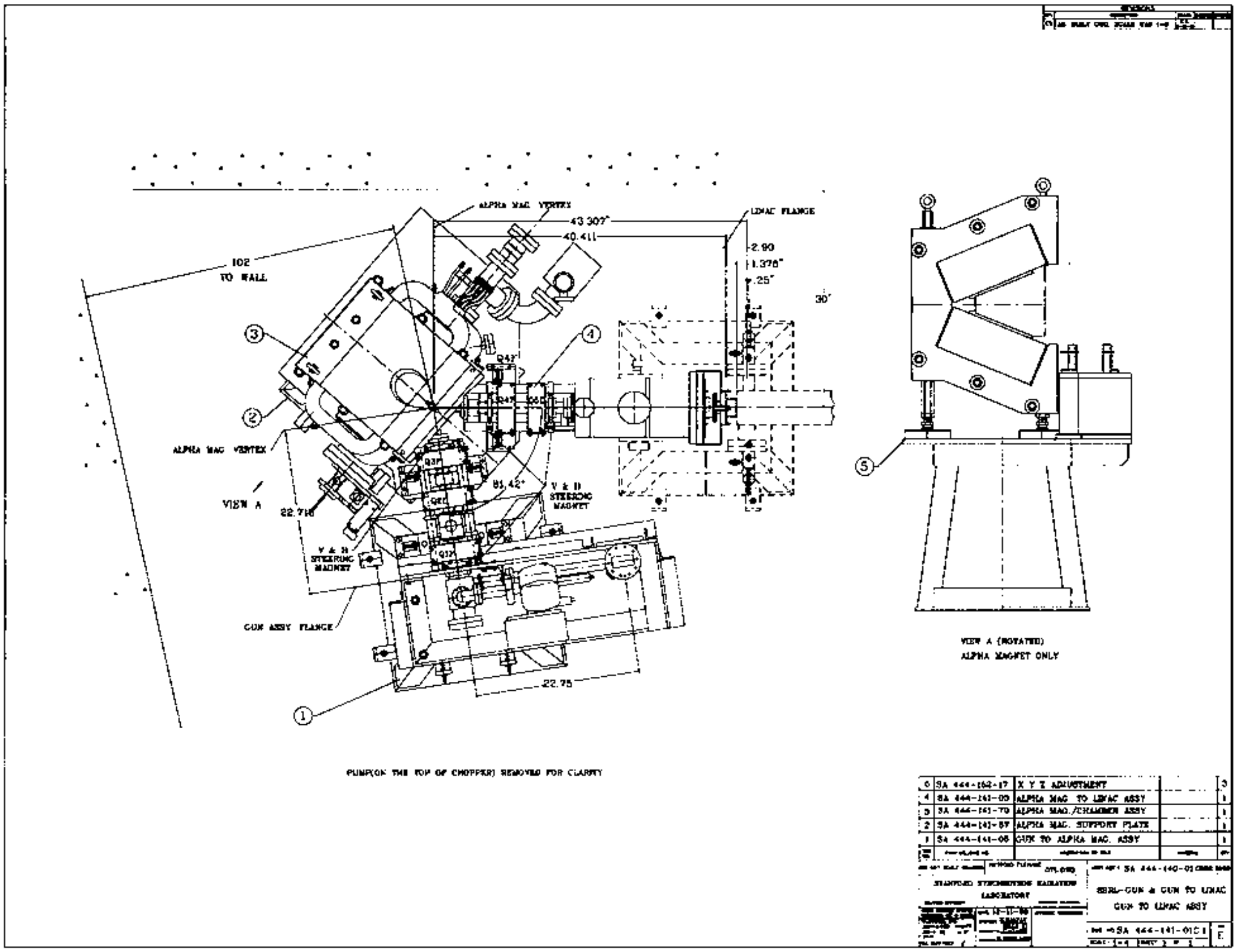

Figure 2. A SSRL Autocad schematic of the Gun to Linac (GTL) setup. This includes the RF gun, a series of quadrupoles, and the alpha magnet.

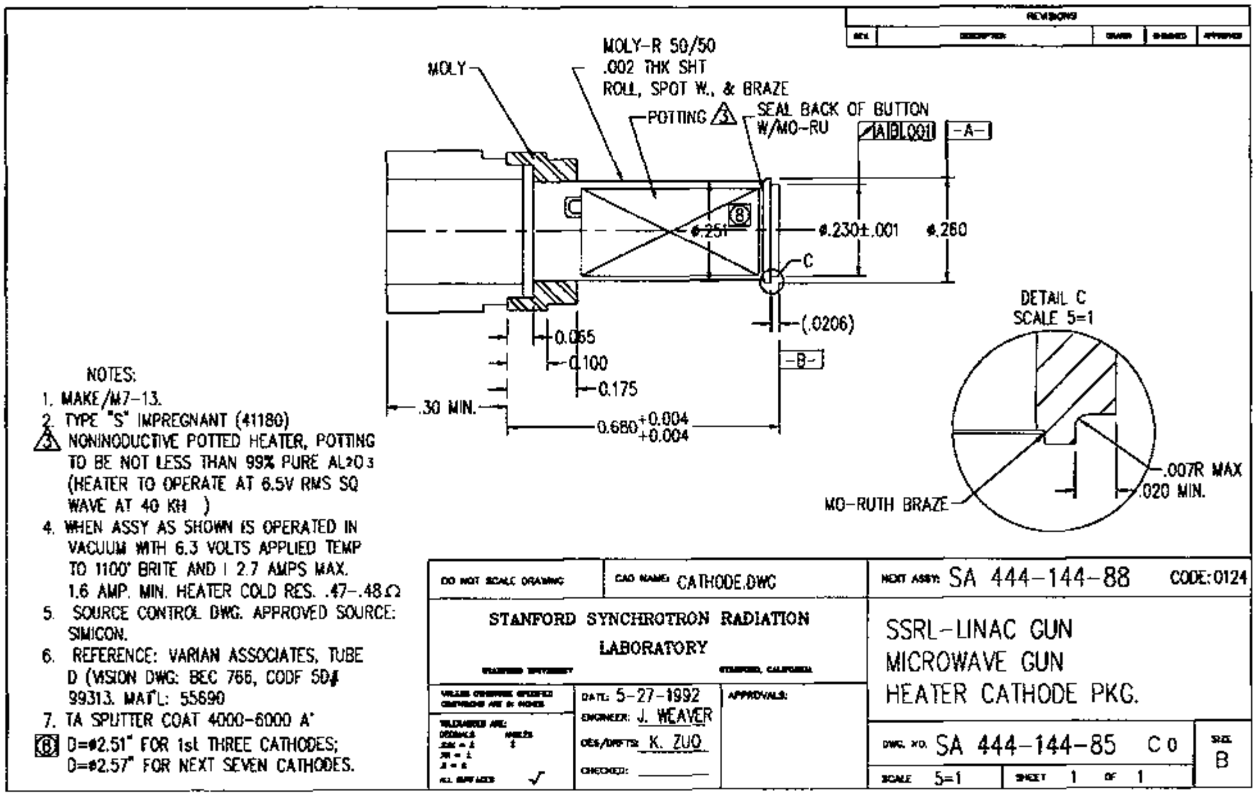

Figure 3. This is an SSRL Autocad drawing of the cathode, also known as the heater cathode package as seen in the title block of the drawing.

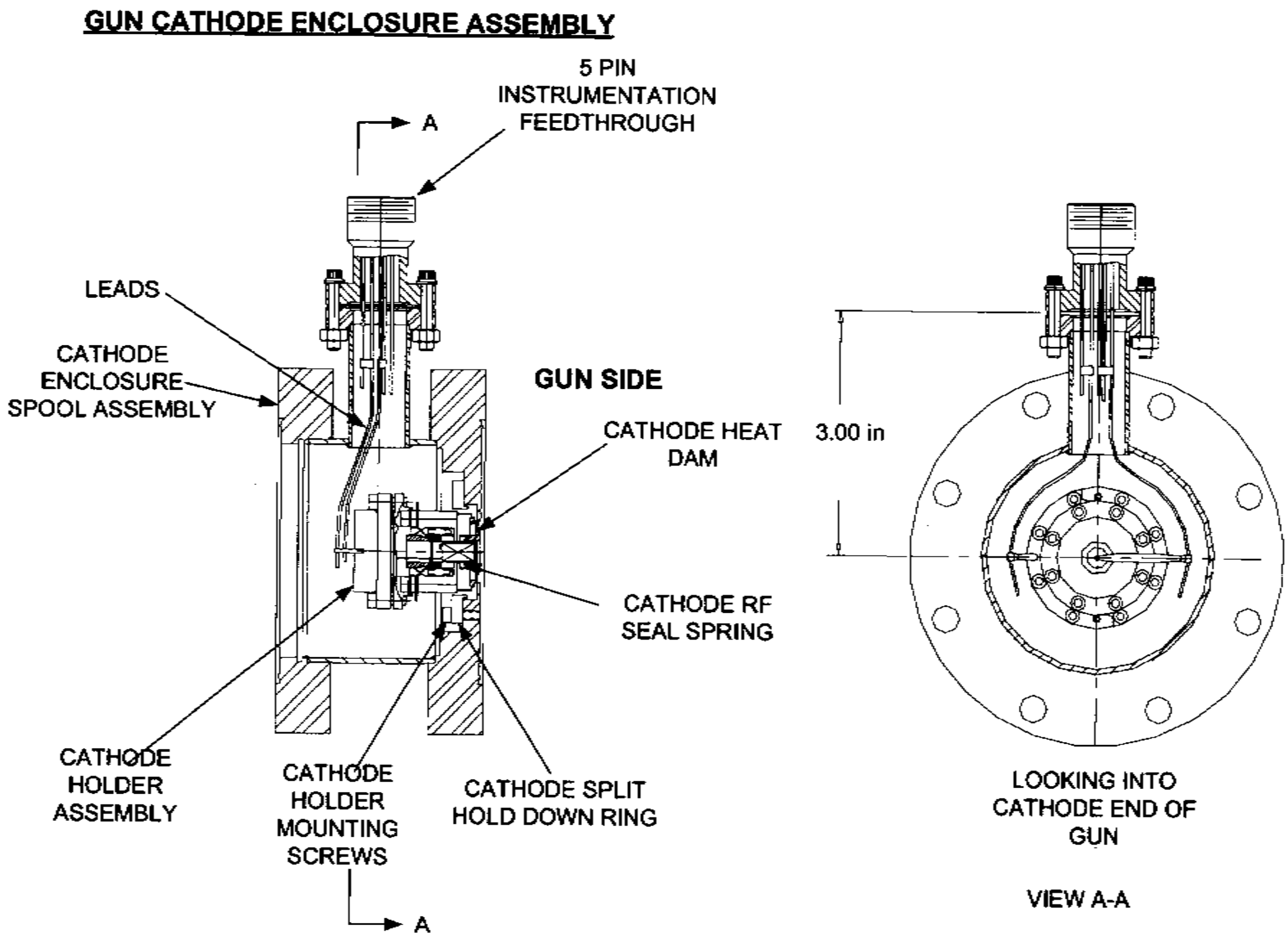

Figure 4. A schematic of the cathode assembly

GUN CATHODE AND MOUNTING ASSEMBLY

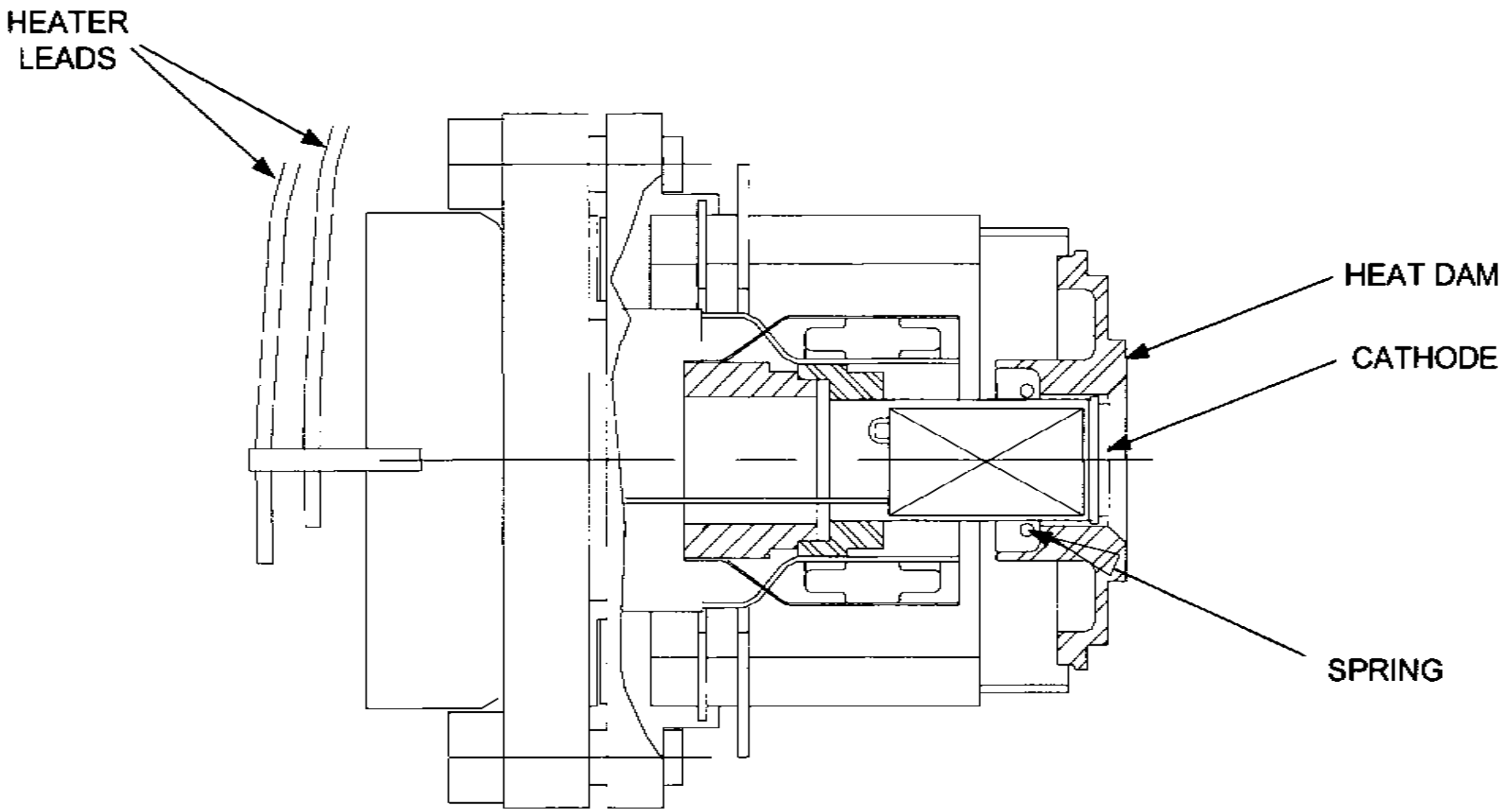

Figure 5. A close up of the cathode assembly enclosure.

Appendix A: RF Gun Details

Overview[†]

The RF Gun

A 1.5 cell thermionic RF gun emits an electron beam of approximately 3000 bunches per micro second of pulse which is digitally set to 10 Hz. The rf-power supplied to the gun is 2 mega-watts (MW) and the beam is emitted with energy of 2.MeV. The cells of the gun are made of copper which can become distorted if the heat of the gun body varies by any degree.

Beam Compression

As stated in the proceeding paragraph, the RF gun emits an electron beam of 3000 bunches per micro second. From the RF gun the beam is sent to the alpha magnet. The alpha magnet compresses the bunches from micro seconds to a few hundred Pico seconds. This is possible because the electrons that are moving at faster speeds are harder to manipulate, so the alpha path the electrons go through is larger for electrons at higher energies, while electrons at lower energies create a more concise alpha path. Therefore, the slower electrons have time to catch up with the electrons that were moving at faster speeds, creating a more succinct bunch. The beam is sent through the chopper that lets only three or four bunches through by deflecting the beam to either of two sides of a magnetic septum. One septum leads to the Booster, while the other leads to a dump.

The Anode

[†] Referenced from The SPEAR Injector RF Gun and Linac Performance by Sanghyun Park (2000)

The anode is a metal plate with a 0.0005" thick copper surface. The anode attracts the electrons since it has a positive charge as compared to the cathode of the gun. The anode is shaped as a circular disk with a hole in the center allowing most of the electron beam to pass through it.

The Cathode

The cathode of the gun is placed in the first wall of the half cell of the gun. The holder of the cathode is made of copper, while the cathode itself is made from porous tungsten. Inside the plug of the cathode there is Barium (Ba), Calcium (Ca), and Aluminum (Al) oxides. There is Osmium (Os) and Ruthenium (Ru) on the surface of the plug to act as a dispensing filter of the Barium. When the cathode is heated to a temperature of 950 to 1000 degrees Celsius, Barium is released onto the surface of the gun to create an even coat of "free" (alkali) Barium that is the thickness of one atom. Since the holder of the cathode is copper, it is given to deformation due to an excess of heat from the cathode due to RF leaking.

The Heat Dam

The purpose of the heat dam of the cathode is to protect the other parts of the gun body from thermal radiation, in other words, it assists in controlling the heat of the cathode. The heat dam used to be made of ceramic which is very effective against thermal radiation, but is a poor vacuum. The current cathode has a heat dam made of Hastelloy, a material similar to stainless steel. Hastelloy lowers the Q value as well as shunt impedance, for this reason the part of the heat dam that "feels" the RF wave is copper plated.

The Spring

The gap between the heat dam and the cathode creates good thermal insulation for the cathode to reach emitting temperature. The only problem with this is that the cathode is now a sort of center conductor of the gun which allows for RF to leak into the back of the gun. This may cause arcing, deform the cathode holder, and/or detuning. A toroid formed from a helix of thin Tungsten wire is inserted into the back of the cathode to shield from any RF leakage. This is the spring of the cathode. The spring not only shields from RF leakage, but it also conducts away heat, therefore, cooling down the cathode.

Feedback Control

Feedback control can be used to restore beam intensity and stability for an ephemeral amount of time when a cathode is experiencing poisoning. The system consists of two gun current toroids, called GT1 and GT2, which provide input parameters to the computer to control the heater power source (PS). Also, two analog-to-digital converters (ADC) run simultaneously and continuously to read GT1 and GT2. This system is used to correct voltage, current, and cathode heater resistance. Only the wave form near the chopper is determined and set to a 10 Hz pulse by software.

Jessica Moore
07/18/02

Interview with Robert Kirby at 10:00 AM

The cathode is made of tungsten metal. The barium in the plug emits electrons. Barium has a low energy barrier and surface potential. Elemental barium is used because of its low energy barrier and the fact that it is very active; if barium is exposed to air it becomes barium oxide with a high energy barrier, therefore not as many electrons would be emitted. When the dispenser is heated the free barium emits electrons. About half of the electrons jump over the barium barrier into the vacuum. If the cathode is exposed to other chemicals, such as air and carbon it will not work, this is called poisoning.

The lifetime of the cathode is determined by the number of barium in the tungsten plug. When the barium becomes less so does the current.

Q: Where does the barium go?

A: Barium has a high evaporation rate. The vapor pressure depends on the temperature of the cathode. It is good if the barium is constantly evaporating because this allows new barium onto the surface that has not been exposed to any damaging chemicals that may still be in the vacuum. The barium could also build up on the grid in front of the cathode or on the anode.

In the tungsten plug are calcium, aluminum, and barium oxides. These chemicals catalyze and the barium decomposes into free barium. The surface of the plug is a layer of osmium and ruthenium (M-type) approximately 4000-6000 Angstroms thick; this regulates the flow of the barium. There is also a barium layer that is an atom thick.

Possible reasons for low emission: Lately, there are ruthenium holes that let the barium be released as barium oxide, which emits poorly. The original cathode vendor was Varian, now the vendor is Semicon. The new cathode has some parts that are copper coated for conductivity. The injector may have oil in it that can be contaminating the cathode. There could be a hydrocarbon loaded atmosphere; this can be checked with an RGA (residual gas analyzer). Another possibility for slow emission is ion feedback, electrons are hitting other elements and ion feedback sputter at the barium and this is not likely. The heater may be poisoning the cathode.

Instruments: Spectra can pinpoint where residual gas poisoning occurs. If a RGA is used chart pressure versus time and can find out if there exists hydrocarbon groups in the vacuum.

Jessica Moore
07/19/02

Interview with Eduardo Guerra at 1:30 PM

The cathode is cracked after the run. The cathode is on the first wall of the half cell of the RF gun and emits into the full cell. The heater of the cathode is 5 Watts and is operated between 2.7 and 3.5 volts.

Instruments: There is software used to correct the beam. If the screen shows a bad beam, then the bend of the beam is adjusted. Or the acceleration of the beam can be adjusted at the beginning by changing the input to the heater.

Changes in the heater: At the start of the run, the heater was 5 Watts; by the end it was 10 to even 17 Watts. They made the linac cold and that worked for a while. When left cold for 22 hours the beam was stable.

Possible Problem: The coil around the cathode (spring) could be heating, shifting, or shrinking,

Suggestion: Cooling may allow more barium to come to the surface, making it more available.

Jessica Moore
07/22/02

Interviews with Harold Morales and Mike Nalls

Interview with Harold Morales at 10:00 AM

Possible problems: There could be something wrong with the heating material. It may be more conductive than originally thought. The number of coils in the spring may need to be adjusted.

Interview with Mike Nalls at 1:05 PM

Semicon slices the front of the cathode so that the emitting surface is flat. The design is Varian that originally has a curved emitting surface. The barium could be leaking out too fast because there is not enough room to heat. The gun is pumped down to $3.3*10^{-11}$ Torr.

Possible problems: At the last run the heat dam was stuck and needed to be taken out by force. When the new cathode went in, the frequency was changed. A chiller was then put on the gun to keep the frequency constant. The frequency of the gun may still not be stable and that would vary the emitted current. The new style of the cathode may not be the most effective design, Varian cathode worked longer with more stability.

Jessica Moore
7/24/02

Interview with Dave Ernst at 10:00 AM

Water system is now a stand alone chiller that seems to work well, about a week ago there was much noise, but now graph shows a straight line at 27.547 degrees Celsius. The stability of the water is very important, seems remarkably stable.

Unit being used: Neslab HX 75A (chiller) with an optional 1kW.

The instability of the gun sounds like a design flaw in the cathode. It seems that something within the cathode (spring, filament …) seems to change when heat is applied. It then returns to normal most times when the gun is given a rest time and allowed to cool (the agreed upon time is 20-24 hours after the run of the day).

The chillers have heaters inside as to achieve and maintain the temperature of 27.547 degrees. Part of the chiller cools, while the other part heats to maintain the temperature and correct frequency. This is more expensive and complicated than the previous system of only heating water.

The variance of the chiller's temperature is at best 3/10 of a degree or less.

Is of the opinion that out-gassing the cathode to get it to run more stable is not a good idea. May cause other damages. Sometimes it does work, but does not want to strain the cathode by over heating it. (Bob Kirby agrees with this – Barium leaves faster, cathode runs out of Ba and may cause poisoning).

Change the water every down time (6-9 months) this makes sure that the water is clean, since in a closed system could be contaminated with algae if not changed. Chiller does not use filtered water like in the LCW, but the water's conductivity is not a problem, not enough minerals to be very conductive.

Jessica Moore
07/30/02

Interview with Ihioma Nzeadibe at 1:30 PM

The cathode heats the rest of the gun body by conduction and convection. There is not that much convection since the air in the gun and outside the gun is stalled (stagnant). Note: the spring and the heat dam assist on conducting heat away from the cathode. The spring is attached to the end of the cathode very specifically (Mike Nalls does this).

Q: What all controls the temperature of the gun body? Is it just the chillers?

A: Yes. The system relies only on the LCW to conduct away heat from the gun body.

Also, heating the gun body by convection depends on how the gun is mounted. If the gun is horizontal, it is likely that more air will flow over the gun, but if the gun is vertical it is highly improbable that air will flow over it, therefore, the air cannot deposit heat to the body.

Q: Is there any way to make the temperature completely stable? Was there a time when the temperature of the gun body, cathode, and the gun frequency was stable?

A: When Jim Weaver was in charge of maintenance the technicians would spend two to three days installing and testing the cathode and gun. In this time they would observe the temperature and make any needed adjustments. Now, they do the same work in about three hours. (Mike Nalls has informed Mr. Nzeadibe of this). Another observation is that before last month the RF and high voltage was left on between runs, this may keep the cathode at a high temperature and cause instability. Once the gun was turned off between runs it began to run stable. (Dr. Wiedemann has always turned the RF and high voltage off between runs).

Recommendations: It seems that the testing time should be extended to the two or three days it used to be. This gives more time to observe the temperature of the gun and cathode and any other inconsistencies that can arise. This may take away from later pains. Also, maybe the cathode should be turned off between runs. If the RF and high voltage is kept on and can keep the cathode at a high enough temperature, then maybe Barium is leaking onto the surface through the cracks that have developed through use. This would cause an unnecessary loss of Barium and would cause the life of the cathode to be shorter.

Jessica Moore
07/30/02

Aspects of the gun and cathode

Sanghyun (Sam) Park

1. For the record, do you know what the ideal current of the gun is, and what has been its lowest performance this year?

A1) The electron current out of the gun is measured in volts, with the conversion factor of 160 mA/V. It is anywhere between 1 to 5 volts. There is no ideal *current since the gun current, which we call GT1 for Gun Toroid #1, is an operational parameter that we change for the best injection rate in terms of mA/min. What is important is the stability. When it is stable, we can fine tune the LTB (Linac to Booster) and BTS (Booster to Spear) magnetic lattice to achieve the maximum injection efficiency.*

2. Where are the heat dam and spring placed in reference to the cathode?

A2) Heat dam shields off the radiating heat from the cathode. Therefore the heat dam is made of an alloy called Hastelloy. It is better than stainless steel in thermal insulation. Of course refractory materials such as molybdenum of tantalum can be used but they are much harder to fabricate. The heat dam as seen from the gun exit is a thin disk with a hole at the center where the cathode emits electrons. At the cathode the accelerating RF electric field is the highest. This means that the electric field energy is well dissipated at the cathode and at the heat dam since the heat dam has low thermal conductivity K, which means that it has low electrical conductivity σ so that the wave electric field penetrate deep into the alloy and gets dissipated. In order to preserve the E-field strength and distribution, the heat dam is plated with copper.
The tungsten spring is an electrical short for the accelerating E-field. Without it, the cathode acts like a center conductor of a coaxial cable, transporting the RF wave energy into the back side of the RF gun causing arcing. So it must be in electrical contact with the cathode. At the same time, it must not conduct away any significant amount of heat from the cathode. Therefore the number of turns in the tungsten coil bent into a toroidal form must be optimized. The spring is placed behind the heat dam and around the cathode, slightly behind the cathode tip.

3. Is there any way the placement of the heater and spring in reference to the cathode can affect the temperature of the cathode and gun or cause any problems?

A3) See A2 above.

4. How exactly does the heat dam and spring control the temperature of the cathode?

A4) See A2 above.

5. How much heat would it take to deform the cathode holder or the cells?

A5) As far as you maintain the heat dam in the right place, it'll be hard to overheat the cathode to the extent that you damage the cathode or the cell of the gun.

The heater power supply is limited in maximum power: the cathode is passively safe. If you are determined to overheat the cathode, the cathode will be the first victim.

6. How would the inconsistency of the temperature of the gun body affect its performance?

A6) We have three boundary conditions in temperature: cathode, cooling water, and the room temperature. Although all three can be changed, what matters is the stability, which translates into temperature gradients that are constant in time.

When the gun is off the resonance, we can bring it back to the resonance by changing the cooling water temperature. Once we are in a good operating regime, we try our best to stay in that regime.

7. What all controls the temperature of the gun body? Is it just the chillers?

A8) Yes, we have a chiller. Actually it is a combination of chiller and heater. Within the rated water flow rate, the temperature deviation (or fluctuation) from the set point is very small (less than +/- 0.1°C). The effect of this fluctuation or drift is not noticeable in the gun performance.

8. Is there anyway to make the temperature completely stable? Was there a time when the temperature of the gun body, cathode, and the gun frequency was stable?

A9) We are generally happy with the temperature control. We don't have a good reason to upgrade our temperature control system. It is good enough as is.

It is doable task to regulate the temperature within, say, one micro degree Celsius. But what do you need it for? For satisfactory operation of our gun, we don't.

9. Seeing the instabilities of the gun, the effects that cooling and outgasing have on the stability, do you have an opinion on what could be causing the problems with the gun?

A10) It is the back bombardment of the cathode surface by the electrons accelerated toward it. In the cell the RF accelerating field changes sign. In a photocathode RF gun, you select a right RF phase to shoot the laser beam of a few picoseconds.

All photo-electrons are accelerated in the right direction. In a thermionic RF gun, on the other hand, the cathode emits electrons at all times. A majority of the electrons make their way out of the gun. But some of them don't get enough speed and have their motion reversed. This is a fact. If we can redirect this back bombardment to a location outside the cathode, we'll have extended period of trouble-free operation.
One possibility is to prepare a cathode with a non-emitting surface on the axis.

This will produce annular beam of electrons. We are actively working on this scheme. Presently the back bombardment damages the cathode and it's the source of all the trouble. The damage is localized, but it is bad enough to cause operational difficulties.

Jessica Moore
07/30/02

Aspects of the gun and cathode

Dr. Helmut Wiedemann

1. For the record, do you know what the ideal current of the gun is, and what has been its lowest performance this year?

   I have no knowledge of the operating conditions for the gun at SSRL. I am using the same type of gun on campus. The cathode current is not the relevant parameter, it's the cathode resistance. As the temperature of the cathode increases, the resistance increases too. The limit is about 3.2 Ohm. Going beyond that means you heat the cathode heater too much and it may break soon. Below this limit, we adjust the cathode current until we get the desired electron beam.

2. Where are the heat dam and spring placed in reference to the cathode?

   The heat dam is a plate around the tip of the cathode. Mike Nalls can show you one. The spring is placed between cathode and heat dam.

3. Is there any way the placement of the heater and spring in reference to the cathode can affect the temperature of the cathode and gun or cause any problems?

   The heater is embedded in the cathode. The spring prevents heat loss from the cathode to the gun. If the spring is squished, the heat loss is too high and it is not possible to reach an operating temperature of about 900 to 1000 deg C. The next piece of material is the heat dam separating the spring from the gun. The heat dam is made of some kind of copper coated ceramic (Hastelloy) which is a bad heat conductor.

4. How exactly does the heat dam and spring control the temperature of the cathode?

   See above.

5. How much heat would it take to deform the cathode holder or the cells?

   There is not enough power available in the cathode heater supply to cause any damage to the gun or holder.

6. How would the inconsistency of the temperature of the gun body affect its performance?

   The gun body has to be kept at a fixed temperature because the size of the gun cells depends on the temperature. On the other hand, the cell sizes determine the resonance frequency, which must be 2856 MHz. The frequency dependence of the gun on temperature is about 50 kHz/deg C.

7. What all controls the temperature of the gun body? Is it just the chillers?

   Yes, the rf-power is too small to make a significant difference.

8. Is there anyway to make the temperature completely stable? Was there a time when the temperature of the gun body, cathode, and the gun frequency was stable?

   Yes, on campus we monitor the temperature of the gun and keep it constant with a feedback system to the gun heater.

9. Seeing the instabilities of the gun, the effects that cooling and outgasing have on the stability, do you have an opinion on what could be causing the problems with the gun?

   I have not looked into the data enough. On campus we have a similar gun, the same cathode and no stability problem. We keep the electron beam constant with a feedback system taking the beam signal from T1 and controlling the cathode heater.

Jessica Moore
07/30/02

Aspects of the gun and cathode

John Schmerge

1. For the record, do you know what the ideal current of the gun is, and what has been its lowest performance this year?

   The ideal current is as much as possible but is typically operated in the 0.5-1 A range. It is always in this range and any large fluctuation is intentional. The feedback circuit keeps the current output approximately constant. However, a small current fluctuation can lead to a significant energy change which operators report as instability.

2. Where are the heat dam and spring placed in reference to the cathode?

   You would need to look at the drawing to answer this question. Sam and or Mike can possibly help you find a drawing.

3. Is there any way the placement of the heater and spring in reference to the cathode can affect the temperature of the cathode and gun or cause any problems?

   Yes I believe the spring can affect the cathode temperature but unless the spring moves over time it will not cause a problem. This was one of the first suspects causing the problem but after removing several cathodes the springs showed no ill effects. Also, it is the same spring used on other identical guns.

4. How exactly does the heat dam and spring control the temperature of the cathode?

   The heat dam and spring control a heat loss term due to heat conduction. If you change the conduction term you will change the temperature and thus emission.

5. How much heat would it take to deform the cathode holder or the cells?

   I don't know how much power it would take to deform the cathode holder but the cathode heater does not have enough power to deform the cell. There is an order of magnitude more RF power dissipated in the cavity than delivered by the cathode heater.

6. How would the inconsistency of the temperature of the gun body affect its performance?

   The temperature of the gun body is constant. However, if the temperature does change it affects the resonant frequency due to thermal expansion. This leads to a change in the RF field value and a resulting change in current and energy.

7. What all controls the temperature of the gun body? Is it just the chillers?

A dedicated chiller/heater controls the gun body temperature. In an effort to control the gun temperature the chiller must dissipate the roughly 50 W of RF power dissipated in the structure.

8. Is there anyway to make the temperature completely stable? Was there a time when the temperature of the gun body, cathode, and the gun frequency was stable?

   The structure is stable. The gun body, temperature and frequency are stable. The cathode lifetime (the cathode typically operates in a stable mode for months) can be increased by decreasing the back bombardment. This will be done during the startup.

9. Seeing the instabilities of the gun, the effects that cooling and outgasing have on the stability, do you have an opinion on what could be causing the problems with the gun?

   After hours of observation of the gun I have never seen an outgasing problem or effect on gun performance. I am not sure what you mean by the cooling effect. The problem with the gun is a rapidly changing emission over a small cathode surface area leading to a small change in emitted current. However, the small change in current leads to a significant change in energy and energy spread due to beam loading. The energy change is the instability the operators report. Compared with other identical cathodes and guns which do not exhibit this problem the problem can be traced to back bombardment due to operating the cathode at a temperature that is too high. Reducing back bombardment will both reduce the energy deposited on the cathode limiting the cathode emission fluctuations and it will also reduce the beam loading leading to less of an effect on energy with changes in current. The feedback circuit will be required to keep the gun operating at its new operating point since it will tend to run away because of back bombardment. I will tune the gun to this new operating point during the start up.

   While we may not understand the chemistry leading to the local current fluctuations, the data is clear that back bombardment is causing the problem.

Jessica Moore
08/05/02

The Feedback System

John Schmerge

1. What parts does the feedback system consist of?

A toroid to measure the current exiting the gun followed by some electronics to condition the analog signal and finally a digitizer to sample the current waveform. After the digitizer the feedback system is all software which then controls the heater voltage depending on the gun output current.

2. Is there anyway you can think of that the feedback system can be improved?

There are perhaps marginal improvements that can be made by determining the most sensitive part of the curve to changes in energy and measuring the current at that point as well as calculating the proper response function so that the correct feedback values can be used in the PID controller. However, all this depends on the operating point used and since the operating point will be changed during the start up nothing can be done until the start up.

3. Is it possible that the feedback system can be affecting the stability of the RF gun?

Yes, the feedback improves the stability.

Appendix C: Cathode History

SSRL Cathode Summary

SSRL #	Other ID #	Type	History	Status
2	None	AET TYPE #1A	3-90: Installed in TrfG #1 SSRL Gun with an alumina heat dam. 7-93: Removed from TrfG #1 SSRL Gun to have the Gun body cleaned by AET.	Not useable, stored in Bld 137 1st @ SSRL '90 - '93 (3.3 yrs)
6	BET504-5	AET TYPE #1B	10-93: Installed in TrfG #3 SSRL Gun w/ hastelloy C heat dam. Very little assembly documentation. 7-95: Removed from TrfG #3 SSRL Gun due to emission problems during the last 6 months of life. Investigation revealed that the cathode was not centered in the heat dam, heat dam spring was not making contact all the way around, and the "green" screws were loose. The cathode tip was badly pitted, and had a melt-crater possibly from back-bombardment.	Not useable, stored in Bld 137. 2nd @ SSRL '93 - '95 (2.0 yrs)
7	BET504-4	AET TYPE #1B	10-95: Installed in TrfG #3 SSRL Gun with a hastelloy C heat dam type IVA. Heat dam spring 25 turns, tip aligned to .036", res. at .586 ohms. Cathode temp 1205C. 8-99: Removed from TrfG #3 SSRL Gun as a preventative measure (possibly at end of life expectancy).	Useable, needs heat dam. 3rd @ SSRL '95 - '99 (4.0 yrs)
25	Semicon #1	AET TYPE #4	12-97: Rec'd from Semicon Associates 7-98 to 10-98: Installed in Dummy Gun for processing, summary test details below: 1st: Heat dam spring 24 turns, tip align to .0375", cold res. .586 ohms. Aborted processing due to excessive back-scattering in cathode housing (cathode tip never got hot). Suspect heat dam spring and/or cathode-to-heat dam alignment. 2nd: New heat dam, rework spring at 24 turns. Cathode temp reached 925C. 3rd: New spring 24 turns, new heat dam, changed other hdwe. Tip align to .039", cold res. .556 ohms. Cathode temp 800C. 4th (test actually): Tested cathode w/o heat dam or spring (temp. easily reached 1100C). 5th: Cut spring to 18 turns, tip align to .035", cold res. .574 ohms. Cathode temp reached 1141C (optimum). 8-99: Installed in TrfG #3 SSRL Gun. 10-99: Cathode emitting unstable emission (seems to be very sensitive to Gun heater temp). 2-00: Cathode assembly removed from TrfG #3 SSRL Gun. Visual analysis: an area of "cracks" and a dark spot on surface. 3-00: Cathode tip analyzed by SLAC Metallurgy (report #727)	2-00: Removed from SSRL Gun, under evaluation. Tip analysis by SLAC Metallurgy 4th @ SSRL '99 - '00 (0.3 yr)
30	Semicon #2	AET TYPE #4	12-97: Rec'd from Semicon Associates 9-98: LaserFab laser welded cathode to tube/flange assembly, Type 2. 4-99 to 5-99: Installed in Dummy Gun for processing, summary test details below: 1st: Heat dam spring 25 turns, tip align to .035", cold res. .586 ohms, tip centered within .003". Temp <700C. 2nd: Rework spring w/forming tool. Cathode temp 970C. 3rd: Rework spring w/forming tool. Cathode temp 850C. 4th: Rework spring w/forming tool. Cathode temp 950C. 5th: New heat dam spring 20 turns. Cathode temp rose too rapidly to 1300C (spring was not contacting the cathode). 6th: Reworked spring w/forming tool (spring lightly contacting the cathode). Cathode temp 1120C (optimum). 2-00: Installed in TrfG #3 SSRL Gun. Processed quickly, but exhibited unstable emission. Beam output became more stable and reliable after ~ 1 week. Cathode emission was periodically unstable during lifetime in Gun. 9-01: Removed as a preventative measure, due to periodic erratic emission (end of lifetime).	9-01: Removed from SSRL Gun, to be evaluated. 5th @ SSRL '00 - '01 (1.5 yr)

SSRL Cathode Summary

SSRL #	Other ID #	Type	History	Status
26	Semicon #2	AET TYPE #4	12-97: Rec'd from Semicon Associates 1-00: Laser welded cathode to tube/flange assembly Type 2 at Applied Instrumentation. 2-00: Installed in Dummy Gun for processing, summary test details below: 1st: Heat dam spring @ 18 turns, tip align to .035", cold res. .562 ohms. Cathode temp 1023C. Cathode at temp ~ 16 hours. 2nd: Reworked spring w/forming tool. Cathode temp 1070C (~20C above minimum). Cathode at temp ~15 hours. 3-00: Pyrometer comparison tests. Cathode at temp during tests ~14 hours. Observations: 1) Cathode did not appear to reach optimum temp (reached 865C thru a darkened view port) 2) Heat dam appears oxidized after the comparison tests. 4-00: Removed from Dummy Gun to inspect the heat dam. After venting Dummy Gun, the "oxidized" heat dam now looked clean, and there was not a black area on the heat dam as originally observed. Reinstall into Dummy gun for processing: 1st: Heat dam spring @ 18 turns, tip align to .035", cold res. .574 ohms. Cathode temp 1040C. 2nd: Rework spring w/.256" tool. Heat dam spring @ 18 turns, tip align to .036", cold res. .578 ohms. Cathode temp 1005C. 3rd: Rework spring w/.256" tool. Heat dam spring @ 18 turns, tip align to .036", cold res. .571 ohms. Cathode temp 975C. 4th: Replace spring, form w/.256" tool. Heat dam spring @ 18 turns, tip align to .036", cold res. .570 ohms. Cathode temp 1009C. 5th: Rework spring w/ .256" tool. Heat dam spring @ 18 turns, tip align to .036", cold res. .570 ohms. Cathode temp 1010C. 5-00: Tested cathode only in dummy gun (heat dam only, w/o spring). Tip align to .036", Res. .562 ohms. Cathode temp 1139C. 5-00: Reinstall with spring into dummy gun for processing: 1st: Heat dam spring @ 18 turns, .256" forming tool, tip align to .038", cold res. .571 ohms. Cathode temp 1106C. RFI in Dummy Gun 2-01: Used in Gun heater power supply tests w/J. Schmerge and S. Park. Run for several hrs. at temp. 9-01: Installed in TrfG #3 SSRL Gun. 2-02: Periodic instability. Replacement discussions circulating amongst system managers. 3-02: Cathode heater turned off for ~6 hrs. during conservation mode. Cathode appeared more stable after startup.	9-01: Begin use SSRL Gun. 6th @ SSRL '01 -