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Thermionic RF Gun and Linac Pre-Injector for SPEAR3 *

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THERMIONIC RF GUN AND LINAC PRE-INJECTOR FOR SPEAR3 *

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Abstract

Preparations are underway to upgrade the Spear2 to the third generation light source. Installation of all the subsystems will start in April 2003. Although the Spear3 RF system is entirely different from the present form, the pre-injector gun/linac and booster synchrotron will remain the same even after the upgrade. The thermionic rf gun reliability and stability are to be improved to inject 500 mA of stored current in shortest possible time. When a top-up mode is enforced, where the stored beam decay is replenished to maintain the constant current and thus constant light intensity, the Spear3 will take injection every few minutes. In that case the gun, linac, and booster must stay on at all times. In this report we will describe some improvements made on the gun and linac in the recent past, as well as their present performance and future upgrade to be made.

1 INTRODUCTION

The Spear at SSRL is presently being upgraded to a third generation light source [1]. Virtually all the storage ring components are to be replaced during a 6-month period starting from April 1, 2003. From the users point of view, the major changes are increased current (500 mA) stored in the ring, lower emittance (18 nm-rad), higher critical energy (7.6 keV), and lower beam life-time (18 hours at 500 mA).

In Spear2, the injection energy is 2.3 GeV [2] so that whenever the ring is refilled the remaining current at 3.0 GeV is dumped to prepare the ring at 2.3 GeV. When the ring is filled up to 100 mA, the beam energy is ramped up to 3.0 GeV. At this point, a global feedback is launched for the beam stability. Then the beam is put into automatic steering, and the photon beam is delivered to the users at every beamline.

With about 40-hour lifetime at 100 mA, the ring is refilled once a day, and the whole sequence shown above is to be finished within 24-minute period. Typically the injection time from 0 to 100 mA is about 10 minutes. The rest is used for bend magnet demagnetisation, energy ramp, and the beam steering.

In Spear3, the injection energy is raised to 3.0 GeV so that there is no need for demagnetisation or energy ramp of the bend magnets. Therefore there is no need to dump the remaining beam at the time of injection. How often the injection is made depends on the user requirements.

Defining a vacuum quality $Q_V = It$, where I is the stored current and t is the beam half-life, Q_V of 9 A-Hr in Spear3 is roughly a constant. If the beam current is to stay above 400 mA, 100 mA must be injected at every 135 minutes. If the injection interval is reduced to a few minutes, the stored beam current stays practically constant. The Advanced Photon Source (APS) at Argonne has been in this top-up mode for some time recently.

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2 GUN/LINAC SETUP

2.1 Tungsten Dispenser Cathode

The SSRL history has it that the Spear ring was filled with electrons and positrons injected by a small portion of the Main Linac in the seventies. Since the commissioning of a dedicated injector in 1990, a thermionic cathode in the RF gun's first half-cell has been the electron source. The dispenser cathode details are shown in Table 1 below:

Table 1. Tungsten dispenser cathode details.

Parameter	Unit	Value	Remarks
Plug diameter	in.	0.250	nominal
Plug thickness	in.	0.065	nominal
Plug porosity	%	20	80% solid W density
Impregnant		[411], S-type	4BaO, CaO, Al_2O_3
Coating		Os/Ru	0.3~0.5 μm thick
Emissivity		0.44	at λ=0.65 μm
Heater wire dia.	in.	0.009	W, 3% rhenium
Cold resistance	Ω	0.54	at 20 ^{o}C
Hot resistance	Ω	2.2~2.3	in operation
Heater power	W	6.7~6.8	60 Hz, AC
Activation temp	^{o}C	1050	chemical conversion

Tungsten powder is pressed into a matrix form to make a dispenser cathode. This porous tungsten is impregnated with barium calcium aluminate. When the plug is heated to activation temperature, impregnant-tungsten reaction in the pores releases BaO molecules. They migrate to the emitting surface and form Ba-O dipole layer. The work function of tungsten at 4.5 eV is lowered to 2.1 eV by the layer. Oxygen is a bonding between barium and tungsten substrate. Without it, barium evaporates quickly.

The osmium/ruthenium coating enhances the dipole in that the work function is further lowered to about 1.9 eV. It also acts as a filter that controls the BaO diffusion so that the pores near the surface is not depleted of BaO.

2.2 Cathode Assembly

Exposing a hot cathode to the high power microwave in an RF gun cell poses a few potentially serious problems. The cathode heat flux must be shielded so the surrounding area does not reach excessively high temperature. A heat dam is machined out of Hastelloy® to serve the purpose.

Hastelloy C-276 has 8.9 g/cm^3 density, 13.4x10^{-6}/^{o}K thermal expansion in 24~538 ^{o}C range, 10~19 W/m-^{o}K of thermal conductivity in up to 1000 ^{o}C, and 1.3 μΩ-m electrical resistivity. It is as easily machined as stainless steel is. The heat dam incorporates axially symmetric 45-degree conic structure around the cathode tip to focus electrons at low energy. Its high electrical resistivity and large skin depth entails loss of microwave power and distortion of the accelerating field structure in the gun. A cure for this problem is to copper-plate the heat dam to 5~10 μm thick where the surface is exposed to the wave.

Use of heat dam inevitably leaves a small gap around the cathode. The cathode is now a center conductor of a coaxial structure, transporting microwave power to the backside of the gun. This will reduce the power available for electron acceleration. More importantly, it will cause arcing at the cathode assembly. An rf seal is installed behind the heat dam and around the cathode casing.

A tungsten wire of 0.007-inch diameter is tightly wound on a mandrel to form a helix of 0.0617-inch O.D. and 142.9 turns-per-inch pitch. It is degreased, fired at 1530 ^{o}C for 15 minutes, and removed from the mandrel. These are commercially available. Then a small portion of it is cut and stretched on a mandrel to make a torus. The cathode temperature strongly depends on the number of poloidal turns in the toroid for a given heater power. For a ¼-inch diameter cathode, the number is 18~24 turns depending on construction details of the cathode and the heat dam.

2.3 Standing-Wave 1-1/2–Cell RF Gun

The existing thermionic-cathode RF gun [2] at SSRL was produced in collaboration by SSRL, AET, and Varian in the late eighties. The design parameters are: 2.856 GHz rf frequency, 4 MW rf power, 2 μs pulse-length for 2 MeV beam energy at 1.5 A, and 1 MW wall dissipation. The coupling coefficient β is thus $\beta = 1+P_{beam}/P_{wall} = 4$. There is an iris at the termination of the waveguide to the full-cell. The existing gun's coupling of β=4, as set by the iris size, causes higher rf reflections due to mismatches at lower beam current.

The rf power from the klystron first fills the full-cell. The half-cell is driven through the side-coupling cell at one side of the gun 90^o away in azimuthal direction from the waveguide. This gives rise to asymmetric perturbation in accelerating field distribution. Compensation is made by a cut-off aperture (used as a pumpout port) on the wall opposite to the side-coupling cell aperture. Hence there is no transverse dipole mode to deflect the electron beam.

2.4 Gun to Linac Transport Line

The electron beam current from the gun is measured by a current toroid. It is followed by an alpha magnet and a beam chopper. After alpha magnet, only 3 bunches are allowed by the chopper to enter the linac for further accelerated to 120 MeV for injection to the Booster synchrotron.

A digitizer reads in the beam current at all times. When triggered, a controller selects a time slot corresponding to the three selected bunches. The average is taken over that time slot and the value is compared with the reference. The error signal controls heater voltage, thus the electron current out of the gun is regulated.

A movable scraper in the alpha magnet scrapes off the electrons with below-cutoff momentum. This turns out to be an important parameter to adjust, especially when the cathode performance is not stable.

The chopper is of travelling-wave type. It is driven by a 7kV pulse with 10 ns risetime from a MOSFET-based pulser. The original chopper-pulser combination is still in use. It has been very stable.

2.5 Linac and Associated Subsystems

Three SLAC-type travelling-wave linac sections, along with the rf gun described above, are powered by a SLAC 5045 klystron [3]. A switching power supply charges up PFN stages in the modulator. Its voltage regulation is excellent. A solid-state amplifier of 1 kW output power provides the rf input. The master oscillator has two parts: OCXO (oven-controlled crystal oscillator) operating at 119 MHz +/- 5 ppm, and a x24 frequency multiplier that puts out 2.856 GHz. It is so stable that all the digits displayed on the frequency counter appear to be frozen most of the time.

There is no beam energy diagnostics until the beam is accelerated to its full energy, and bent into the LTB (linac to booster) line. After the bend magnet is a beam profile monitor that displays the linac beam intensity and its energy distribution. The switching power supply voltage is adjusted to control the klystron beam power. It in turn changes the linac beam energy if it is not at optimal value.

3. OPERATIONAL EXPERIENCE

Since the klystron beam power fluctuation or drift is negligible and the rf input to the klystron is strong enough to be in a klystron saturation mode, the klystron output power is quite stable as it is monitored on a TDS-type oscilloscope. The power branching ration is fixed among the three linac sections. Although the rf power to the gun is manually and independently adjustable, it was set at 3.0 MW. Therefore all four accelerating structures receive a fixed amount of rf power. Furthermore, there is virtually no beam loading at the linac. Yet, the linac beam energy fluctuation is evident on the beam profile monitor at times.

3.1 Linac Beam Energy Instabilities

The linac beam energy instability usually coincides with the change in the heater resistance. Even with the heater power feedback control enabled, the resistance stays fairly steady at 2.3Ω when the linac beam energy distribution is stable as seen on the beam profile monitor downstream of the first bend magnet. It takes a day or so for heater resistance to decrease by ~15%. Then the linac beam energy has double-peak distribution. The energy separation of the two peaks oscillates irregularly.

3.2 Thermionic Cathode Degradation

Every old cathode taken out of the gun for replacement shows an area of damaged surface, about 0.9 mm in diameter and about 0.8 mm from the cathode center. It's toward the bottom of the gun, whereas the waveguide feed is from the top. In an axisymmetric gun, all the reflected electrons are supposed to land at the cathode center. One possibility is stray magnetic fields of the nearby klystrons or VacIon pumps. Or it can be from the heater wire if the inductance is non-zero.

4 PROPOSED REMEDIES

For the thermionic cathode to be reliable and long lasting, mitigating the back-bombardment is a must. I can be done in two ways: Running the cathode cooler and redirecting the reflected electrons to the non-emitting surface.

Since the cathode is not visible once it is installed in the gun, how the damage evolves in time is a subject of speculation. It seems a reasonable conjecture, however, that the damage is severe enough when heater resistance changes. Therefore, the heater resistance is an important parameter to monitor.

4.1 Cooler Cathode

This is to reduce the total inventory of the electrons by lowering the heater power, or by turning it off between the injections. Lowering the cathode temperature results in reduction of the electron emission, but then the power associated with the back-bombardment is also lowered. As far as the total number of electrons arriving at the linac is within a useful limit, the lower emission is preferred in terms of cathode preservation. Stability is much more important than intensity in that one can fine tune the GTL (gun to linac) and LTB transport lines based on stable beam out of the gun. With reduced beam loading, the rf power set for the gun must also be reduced accordingly. When the cathode performance is stable at the early stage of its life, the optimal rf power level is to be found by plotting the linac intensity against the rf power to the gun.

4.2 RF Manipulation

Since the major issue here is to minimize the electron back-bombardment in the presence of time-varying field, one option is to turn the rf off when the electron emission is not needed: When there is no rf field, there is no back-streaming of electrons. This "rf off" has advantage over the "cathode off" scheme in its agility. When the cathode is turn on from cold, it takes minutes to full emission, whereas rf can be turned on or off in no time at the rf input to the klystron. This feature is significant when the ring is filled in top-up mode, where injection is needed for a few seconds in every few minutes.

4.3 Magnetic Shielding

Once the back-streaming electrons can be brought to the cathode center, as particle simulations indicate, the central spot can be replaced with a non-emitting plug of tungsten of molybdenum. This type of dispenser cathode generates hollow electron beams. They are commercially available for the applications where the back-streaming ions must be taken care of. As explained above, all stray magnetic fields must be shielded out by wrapping the gun with a mu-metal sheet. This shielding is mostly adequate against external fringe fields.

However, there can be internal source - some inductive portion of the heater winding. The heater is powered by an AC power supply (PS) to remove the possibility of cathode electrolysis. If a phase-sensitive triac is added to the PS output stage, the heater can be completely turned off briefly at the beginning of every AC cycle. This has no effect on the cathode temperature, but the electrons accelerated back to the cathode are not subjected to any magnetic field from the heater coil.

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http://other.nrl.navy.mil/CREBWorkShop
http://www.ee.ualberta.ca/icops2002/
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