

# CLS RF Design Note

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(formerly CLS 2.1.4 Rev. 0)

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## REVISION HISTORY

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B	1999-5-15	Original Issue	R. M. Silzer
C	1999-12-24	Update to Super Conducting RF	R. M. Silzer
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## 1. Introduction

The primary function of the radio frequency (RF) systems in the Canadian Light Source (CLS) rings is to supply sufficient accelerating energy to the circulating beam. Another major component of the RF power is used to make up for synchrotron light losses in the dipoles and insertion devices in the storage ring. As well, a certain amount of RF is used to compensate for energy lost to the vacuum structure as coupled through the ring impedances and dissipated via the vacuum chamber wall currents. The RF is also a key factor in determining the beam lifetime and beam stability. Significant RF overvoltage is required to increase the longitudinal acceptance of the ring, thus increasing the Touschek lifetime. Finally, one of the major factors in determining the longitudinal focusing of the ring are the RF characteristics.

## 2. Choice of RF frequency

There are a number of considerations in the choice of an RF frequency for the booster and storage ring. The RF system requires very high CW powers in the hundreds of kilowatts range. Thus, the chosen frequency must be in a range where large power amplification is possible. There is also a timing consideration. Using a frequency that is a fraction of the linac frequency is preferable. Our choice for frequency is between 476 MHz and 500 MHz. Although 500 MHz is not a fraction of our linac frequency (2856 MHz), 500 MHz sources are more available and it is a frequency that many synchrotron light sources and other accelerator facilities have utilized. A limited number of 476 MHz systems are available and are in service at PEP II (B-factory) and at the Brazilian light source.

The use of a 476 MHz master frequency simplifies the timing with exactly six linac bunches corresponding to 1 bucket in the booster and storage ring. However, the use of 476 MHz effectively limits the CLS to the B-factory cavity design or to a unique CLS cavity design. Even when the linac frequency is matched, injection of a bunch train will result in inefficient capture of the beam in the booster. To minimize this, it is advisable to install a chopper just after the linac gun to eliminate electrons that will position themselves far away from the center of the booster RF bucket.

The use of 500 MHz is not nearly so limited by the number of cavity and amplifier options as is the 476 MHz option. The use of a 500 MHz system also opens up the possibility of using superconducting (SC) RF cavities for which there are existing designs at 500 MHz. Along with the numerous normal conducting (NC) cavities used at such facilities as BESSY, ALS, ELETTRA, SRS, and the Photon Factory, to name a few, there is currently a very good 500 MHz SC cavity design being used in CESR at Cornell University. At 500 MHz, matching the linac beam to the booster is a little more difficult and will require a 500 MHz chopper to be used. The added complication is that the linac frequency will not be linked to the booster ring and storage ring RF frequency. This will result in some modulation of the electron bunch current that is accepted into the booster. The availability of 500 MHz technology makes it our preferred choice for the RF frequency for both the booster and the storage ring.

The RF should use a 500 MHz master oscillator. The amplified 500 MHz signal will be distributed to each klystron station via a phase stable line and tapped using a directional

coupler. Although both rings will be constructed to be an integral number of wavelengths at 500 MHz, in practice, the optical lengths of the machines will differ from their design lengths. The master frequency will be adjusted to match the length of the storage ring and both the booster and storage ring RF will be run at this frequency. The existing 2856 MHz oscillator will continue to feed the linac

### **3. RF Voltage in the Storage Ring**

The minimum RF voltage required is determined by the ring energy loss which is greatest at 2.9 GeV. When only dipole losses are considered the storage ring energy loss is 875.9 keV/turn. With the additions of insertion devices, an energy loss of about 1.1 MeV/turn is a better estimate. Additional voltage is needed for beam stability and increased beam lifetime. Lifetime simulations at 2.9 GeV and 0.5 A circulating current in the bare storage ring lattice give adequate Touschek lifetimes in excess of 100 hours at 2.4 MV RF gap voltage and a coupling of 10%. Although this may seem excessive, at 1% coupling, the Touschek lifetime was decreased to around 30 hours. This value is more in line with the gas scattering lifetimes.

Typical power dissipation in a normal conducting cavity is about 75 kW for conventional designs. This limits the RF voltage per cavity to about 800 kV. (The ELETTRA cavities use 600 kV/cavity, the ALS uses 750 kV/cavity, while the B-factory can approach 1.0 MV). This means that to get a total gap voltage of 2.4 MV we need a minimum of three or four cavities in the main ring.

Superconducting cavities can provide significantly higher CW gradients than NC cavities. In our case, and based on the Cornell design, the full 2.4 MV target voltage can be achieved with only one SC cavity

### **4. Power Requirements**

To assess the power requirements of the RF system we must look to the situation of highest RF load, which occurs when the machine is running at 2.9 GeV with a stored current of 0.5 A. At 0.5 A and with a 875.9 keV/turn energy loss, this gives a beam power loss in the dipoles of 438 kW. We can expect the addition of insertion devices to add roughly another 100 kW of energy loss. Assuming ~10 kW losses to the beam impedances, this gives a total of approximately 550 kW. To determine the installed powers we can estimate a 10% power losses in the waveguide run and that the klystrons will be run at a maximum of 90% of their rated powers to leave them running in the linear region and allow for more effective control. The power requirements for three different cavity options are outlined in Table 1.

**Table 1 Storage Ring RF Power Requirements**

Number of cavities	Cavity voltage (MV)	$P_{\text{cavity}}$ (kW)	$P_{\text{beam}}$ (kW)	$P_{\text{cavity + beam}}$ (kW)	$P_{\text{total}}$ (kW)	$P_{\text{installed}}$ (kW)
B-Factory NC (476 MHz)						
3	0.8	100	183	283	849	1040
4	0.6	56	138	194	776	950
ELETTRA NC (500 MHz)						
5	0.48	36	110	146	730	892
6	0.4	25	92	117	702	858
Cornell SC (500 MHz)						
1	2.4	nil	550	550	550	670
2	1.2	nil	225	225	550	670

At full machine operating current, the power levels are very large and lead to a problem. Most conventional cavity designs experience problems achieving over 150 to 200 kW of power through the input couplers. The B-factory cavities have obtained much higher power levels through the input couplers (of the order of 400 kW). Three B-factory cavities are sufficient to achieve our design current. The ELETTRA cavities have only been operated at 65 kW/cavity. The Swiss Light Source plans on operating these cavities at about 115 kW with the possibility of reaching 150 kW/cavity. This is based on input coupler tests that have reached 330 kW. This means we would require about six ELETTRA cavities to obtain our required power levels. The power handling capability of the Cornell SC cavities is limited by the input window. The windows currently used at Cornell have been conditioned to 450 kW in a test setup. An installed window has been run at 265 kW and in the near future the window will be pushed to higher power levels. Thus, we currently would require two superconducting cavities to reach our design goal of 500 mA, although there is the real possibility that in the future full operation may be accomplished with only one cavity.

## 5. Cavities

In choosing the number and type of cavities to achieve the RF voltage we require, we are making a number of trade offs. Spatial constraints and installation costs both favor fewer cavities. Also, single bunch beam stability is better due to the smaller effective broadband impedance for a fewer cavity system. For normal conducting cavities, the more cavities used, the lower the operating costs. This is due to the large amount of dissipated

power in the cavity bodies when running them at high voltages. Superconducting cavities have negligible power dissipation in the cavity and thus have lower total power consumption including the power used in the refrigeration system.

For a third generation synchrotron light source with currents in excess of a few hundred milliamps, coupled bunch instabilities become a growing concern. These coupled-bunch instabilities are a consequence of the higher-order-mode (HOM) spectrum in the RF cavities. For one bunch to affect another, the wake field generated by the bunch must persist until subsequent bunches pass the same location. This occurs primarily at positions of very high Q such as the RF cavities. For this reason, the cavity choice falls between a SC cavity, or a NC cavity that has an effective treatment of the HOM spectrum either through damping or tuning of the HOM spectrum.

In our design, spatial constraints are a major concern due to the limited number of available straights. As well, minimizing the broadband impedance for stability considerations make the choice of fewer cavities a desirable one. As stated earlier, fewer SC cavities are needed to obtain the same gap voltages. With the current SC cavity and cryostat design (~3.5m), only one SC cavity can be located in one straight. The NC B-factory cavities are in excess of 1.5m long and it would be very difficult to fit more than 2 cavities in a straight. ELETTRA cavities require about 0.9 m/cavity and four would likely fit in one straight. The SC cavity has a longitudinal HOM spectrum strength that is an order of magnitude less than in the NC cavity. Calculations at 500 mA initially suggest that longitudinal feedback to combat coupled bunch instabilities may not be necessary if SC cavities are used but will be needed with NC cavities. This further increases the spatial requirements for a NC system. The 500 mA design goal in the storage ring at the CLS will not likely be achieved for several years. The original operational goals are to reach a level of 200 mA circulating current. In order to obtain the required voltage and power levels for 200 mA operation, three B-factory cavities or four ELETTRA cavities are required while only one SC Cornell cavity is needed.

The Canadian Light Source is on a very aggressive time schedule. This dictates that we prefer to go with a proven cavity design from a recognized vendor. Although the B-factory cavities are a proven cavity, their manufacture is difficult, putting the cost of their fabrication on par with the proposed SC system. An ELETTRA cavity system is also very expensive due to the involved tuning system and the larger number of cavities needed. There exists competent vendors that are willing to manufacture either the B-factory cavities or the Cornell cavity and cryostat. The SC cavity testing can also be accomplished by these vendors, whereas other arrangements would have to be made to test the B-factory cavities. The situation is less clear with the ELETTRA cavities although it is assumed that manufacturing arrangements could be made.

Based on the above discussion the SC cavity appears to be the best option for our ring.

## **6. Superconducting Cryogenic Requirements**

The use of superconducting cavities in the CLS storage ring would require the use of a sizeable refrigeration system to supply the liquid helium(LHe) that cools the cavity to about 4.5 K. The philosophy we are adopting is to have a cryogenic system with a generous

amount of overcapacity, a sizeable amount of LHe and gaseous He storage, and a very high reliability to limit the amount of downtimes encountered.

The Cornell cavity and cryostat has a dynamic heat load given by  $100 \text{ (W)} \times [V(\text{MV})/3.0 \text{ (MV)}]^2$ . The static heat load adds an additional 30 W of cooling. If we are running 2 cavities, the highest voltage would likely be about 2.0 MV per cavity. This results in a total heat load per cavity of about 75 W. Commercial LHe transfer lines require about 1 W of cooling per meter whereas the “home-made” transfer lines at Cornell require only 0.5 W/m. We are tentatively looking at a distance of 50 m from our refrigeration unit to the SC cavity location. For sizing our LHe system we will use the 1 W/m number. Initial thoughts are that the refrigeration unit should be sized to supply two cavities even though only one cavity may be installed initially. In determining the size of our refrigeration unit we will utilize a factor of safety of 1.5. Thus, our total cooling required is  $1.5 \times 2.0 \times (75 \text{ W} + 50 \text{ W}) = 375 \text{ W}$  using commercial transfer lines. A more detailed preliminary design of the system must be done to size the installed refrigeration system. This will also take into account other budgetary considerations.

There will also have to be a sizeable He supply available if we want to avoid lengthy downtimes. The cryostats require about 500 liters of LHe each. It is advisable to have a gas storage unit large enough to contain more than two times the entire cryostat inventory. Under normal operation, the gas storage would only be approximately half full. The LHe storage capacity should also be large enough to store in excess of the total cryostat inventory. Under normal operation, we would have enough helium to fill the cryostats two more times, once from the LHe storage and once from the gas storage reserves. In the case of a planned warm up, the He inventory from the cavity cryostats can be stored in the gas storage and LHe storage facilities. As a rough guideline, one liter of LHe will take up about 2.3 cubic feet (65 liters) at 200 psi (1379 kPa). A LHe storage unit in excess of 1000 litres, and two 3000 cubic foot (85000 liter) gas tanks should be more than adequate. The exact storage requirements will have to be revisited in the future when cost and space requirements are better defined.

In configuring the cryogenic system there are a few things that must be kept in mind. Reliability of the system is of the utmost importance. As well, the refrigeration unit must conform to the vibrational requirements of the CLS. To minimize vibrations, we would like to restrict the use of reciprocating machinery although they are not ruled out due to their lower cost. Turbine liquifiers, although much more expensive, require far less maintenance and have a longer running life. To increase reliability, the use of two liquifiers running in parallel would allow for maintenance to be done on one unit without major interruption to the operation of the storage ring. This redundant system is likely not necessary if a turbine system is used, but may be more attractive if a reciprocating system is implemented. It may be feasible to have a combination of a main turbine system with a reciprocating back up. The exact system will have to be studied either in house or by an outside group to find a balance between cost and reliability.

## **7. High Power Distribution**

The power distribution is accomplished by commercial WR-1800 aluminum waveguide. The exact physical layout of the waveguide runs is not currently determined. Each klystron will be followed by a circulator to protect it from reflected power from the

cavity and to allow it to see a constant load. All waveguide will be under a pressure of about 10 Pa using dehydrated air. Pressure gauging of the waveguide can be used as a rough diagnostic for faulty waveguide connections. Arc detectors will be used to look down all straight runs of waveguide. An infrared temperature detector will be used at both the klystron window and at the cavity window to monitor the window temperatures. Adequate flex sections will be used to allow for easy mating of the waveguide and to allow for some temperature expansion. All bends should be accomplished with the use of mitred bends as they have a lower VSWR and are dimensionally smaller than sweeps. Waveguide hangers can be fabricated with simple threaded rod supports. More elaborate hanging systems using springs etc. are only required for outside installations. There will be a water-cooled load located on each reflected circulator port. There will be a dual directional coupler located just after the klystron outputs and one just prior to the cavity input for monitoring of RF power.

The waveguide layout near the cavity will be the same as that at Cornell. This is a proven system that will be supplied along with the cavity and cryostat. This system includes a vacuum window supplied by Thomson. Prior to this window there will be a small section of waveguide containing dry nitrogen, held by a kapton window capable of withstanding the ring vacuum. Thus, in the case of a vacuum window failure, the rest of the system will only be exposed to dry nitrogen.

There are a few different options that have to be considered in determining what klystrons we will require. For the storage ring we will use one klystron per SC cavity. The klystrons will be located inside the interior of the booster ring. We will initially be running with only one cavity installed and thus one klystron in service. Our initial operating currents will likely remain at a maximum of 200 mA for a number of years, and thus it may be reasonable to use a 300 kW klystron for the storage ring.

Simplistically, there are two different methods of controlling the output power of a klystron. One method is to control the drive power and this controls the RF output power. In this method, the klystron beam current remains constant and any power that is not coupled out of the RF port must still be cooled at the collector. Modulating anode control is an option supplied by many klystrons. The modulating anode requires a high voltage feed to provide control over the klystron beam current. Thus, if less RF power is required, both the RF output power and the power dissipated at the collector are reduced. This method can offer significant power savings over the system where the power is accomplished by controlling the RF drive. The use of modulating anode control will have to be examined with respect to the control system used, and the bandwidth required for RF amplitude control.

## **8. HV Klystron Power Supply**

The klystrons require an adjustable voltage regulated power supply for commissioning and conditioning. This can be accomplished using an adjustable AC supply (0-600 V) feeding a step-up transformer, rectifier, and filter network. Transformers or inductors with oil insulation should be located outside the building. It is desirable to avoid oil insulated transformers. Dry type transformers and inductors could be located near the klystrons, which would simplify the high voltage distribution and reduce stored energy on the distribution lines. Other supplies connect a large number of low voltage switching supplies

in series. These can have very low stored energy and very fast turn off times, which may eliminate the requirement for a crowbar system.

Typical HV power supplies provide 1% voltage regulation. The mod-anode supplies typically offer better than 0.5% regulation. A typical effect of ripple on one high power klystron is a 7 degree phase shift for a 1% change in cathode voltage, and 2.6 degree phase shift for a 1% change of beam current. The RF control system can compensate for these shifts if necessary. There is a tradeoff between the power supply regulation requirement and the required compensation provided by the RF control system.

The klystron will contain a modulating anode grid to vary the klystron current. This feature allows variable input/output power without varying high voltage.

If required, the supply will have crowbar protection to remove power from the klystron if a major fault such as a VSWR , waveguide arc, or other error as specified by the klystron manufacturer occurs. A thyatron-based system designed to meet the manufacturers specifications (typically a crowbar firing time of  $\sim 10$   $\mu$ sec) is required. This system must also switch off the klystron high voltage within 100 msec. Similarly, under a fault condition, a pin diode could block the RF drive in about 1  $\mu$ sec .

## **9. Low Power Control**

The RF will be supplied to each RF station via a phase stable line and a RF coupler. The coupler will be followed by a phase shifter for local station control.

There are a number of different feedback loops that will be employed in each RF station. The RF feedback paths should be designed as short as possible to allow for optimum control. The specifics of the RF control system have to be studied and the exact details have yet to be established. A primary consideration in the effective operation of the storage ring is accurate control over the phase of the RF in the cavity. It is an option to control the phase around the amplifier to compensate for phase changes with varying amplifier conditions. Phase oscillations in the cavity can cause instabilities in the longitudinal plane. Phase feedback from the cavity to the input of the amplifier can be used to overcome this problem. Voltage control in the cavity is also a requirement. This can be done with an amplitude feedback loop that keeps the cavity voltage constant while allowing the cavity power to vary as the beam loading varies.