

**CLS COMMISSIONING –PHASE II
LTB (from OP2), Booster and BTS (to BTS dump)**

Technical Procedure 8.7.90.2 Rev 0

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LTB (from OP2)

1.0 PURPOSE

This section of the report describes the principal components of the linac-to-booster transfer line (LTB) and the actions required to commission this line to meet its requirements as the second stage of the injection system of the Canadian Light Source (CLS). The section of the LTB transfer that is housed in the original SAL vault has been described earlier¹. In that report, the LTB up to optical point 2 (OP2) was described. At OP2 the beam is bent, for the first time, in the vertical direction for transport from the linac vault to the floor of the new CLS facility, specifically to the booster injection point in the booster tunnel.

Requirements are to transport a pulse train of electrons from 2 to 136 ns in duration with a beam energy of 200 to 250 MeV and an average beam current, in the pulse train, up to 60 mA. The beam will have horizontal and vertical emittances not exceeding 0.3 mm-mrad and an energy spread of 0.15% or less. The pulse train contains bunches of electrons at a frequency of 2856 MHz. The phase spread in each bunch (from the Energy Compressor System) is about 120 degrees. The transfer line must focus the beam at the injection point of the booster in such a way that the beam functions are matched to the machine functions of the booster ring. At the entrance of the booster injection septum these functions are: $\beta_x = 2.93$ m, $\alpha_x = 1.41$, $\beta_y = 13.94$ m, $\alpha_y = -2.53$, $\eta_x = 0.26$ m, $\eta_x' = -0.05$, $\eta_y = 0$ m and $\eta_y' = 0$.

This report also describes the requirements for safely commissioning and operating the LTB. Due to the levels of radiation produced by possibly mis-steered beams during transport, the LTB must be enclosed in a secure area. Thus, at OP2, the LTB is enclosed in the former SAL vault. From this point it is bent upward to a tunnel that leaves the linac vault area. In this tunnel, the LTB proceeds at a constant level for some tens of meters under the floor of the new CLS facility until it is once again directed vertically to the CLS floor. At this point, the LTB is inside the booster tunnel. The tunnels serve to exclude access to the LTB environment while the injection system is in operation and to shield the environment external to the tunnels from the radiation that is produced. As well, access to the secure area must be restricted until the residual levels of radiation have been measured and safe working conditions have been established.

2.0 BACKGROUND

The purpose of this report is to provide an overview for the commissioning and operational procedures of the LTB required to safely and efficiently transport a beam of electrons suitable for injection into the CLS booster. The LTB is composed of many components that have to be tested and deemed ready for the commissioning process. Details of these components are found in the references provided throughout the report.

The report includes all aspects of LTB operation from OP2 to the booster injection point. All the components required to transport a beam suitable for injection into the CLS booster are described. OP2 is located in room 0004 (formerly EA3) and is the last position before the beam is bent vertically for transport to the CLS booster. Hence, commissioning of the LTB from OP2 begins with directing the electron beam toward the ceiling of room 0004. To avoid hitting the ceiling, it is mandatory that the dipole magnet that redirects the beam into a horizontal plane (B0108-01) is **ON** with the **correct polarity**. **Commissioning of vertical transport requires detailed monitoring of radiation levels on the CLS floor exterior to the LTB tunnel and the booster tunnel and on the top of the roof of the LTB tunnel.**

3.0 DEFINITIONS AND ABBREVIATIONS

p	pico (1×10^{-12})
n	nano (1×10^{-9})
μ	micro (1×10^{-6})
m	milli (1×10^{-3}) or meter
k	kilo (1×10^3)
M	mega (1×10^6)
G	giga (1×10^9)
eV	electron Volt
rad	radian
s	sec
A	Ampere
W	Watt
Hz	Hertz
RF	Radio frequency
ESS	Energy Spectrometer System
LTB	Linac-To-Booster transfer line

BTS	Booster-To-Storage Ring transfer line
EA3	Experimental Area 3 (Room 0004)
OP	Optical Point
TRM	Transition Radiation Monitor
BPM	Beam Position Monitor (button monitor)
SLM	Stripline Monitor
ICT	Integrating Current Transformer
FCT	Fast Current Transformer
PCT	Parametric Current Transformer
TLD	Thermo Luminescent Dosimeters

Other elements are defined in the CLS Names and Numbering Convention².

4.0 REQUIRED EQUIPMENT

The LTB is described in detail in references 3 and 4. It consists of four (4) modules. Modules 1 and 2 transport the beam from the linac to OP2. Modules 3 and 4 transport the beam from the linac vault to the CLS floor. This section of the report describes modules 3 and 4. Drawings and diagrams for the LTB are listed in Appendix A.

4.1 MODULE 3

The primary components of module 3 begin with a dipole magnet (B0004-01) that bends the beam 21 degrees upward. (see drawings LTB1/ME/0034407 and 0034408) After rising 3.25 m a second dipole magnet (B0108-01) bends the beam 21 degrees back into a horizontal plane. Between the two dipoles is a quadrupole triplet (QD0004-02, QF0004-02 and QD0004-03) used to create an achromat through this module. After the second dipole, there are two more quadrupoles (QD0108-01 and QF0108-01). These two quadrupoles focus the beam at OP3 at the end of Module 3.

4.2 MODULE 4

The primary components of module 4 begin with a quadrupole magnet (QB0108-01) immediately following OP3. (see drawings LTB1/ME/0034408 and 0034605) This is followed by a dipole magnet (B0108-02) that bends the beam 30 degrees upward. After rising 3.3318 m, a second dipole magnet (B1300-01) bends the beam 30 degrees downward back into a horizontal plane. (The beam is now at the elevation of the booster and storage ring.) Between the two dipoles is a quadrupole triplet (QD0108-02, QF0108-02 and QD0108-03) used to create an achromat through this module. After the second dipole, there is a quadrupole doublet (QD1300-01 and QF1300-01) and another quadrupole (QB1300-01). These quadrupoles are followed by two dipole magnets (B1300-02 and B1300-

03). Each of these dipoles bend the beam 42.5 degrees horizontally (a total bend of 85 degrees), directing the beam toward the booster injection septum. Between these dipoles is a single quadrupole (QF1300-02). After the second 42.5 degree bend is a final quadrupole (QB1300-02). This quadrupole is followed by a length of beam pipe that brings the beam to the beginning of the booster injection septum of the end of module 4.

4.3 TIMING SYSTEM

No timing signals are required for modules 3 and 4 of the LTB.

4.4 STEERING

To efficiently transport the electron beam through modules 3 and 4, steering elements are required. After OP2, eight pairs of horizontal and vertical steering magnets are located along the transfer line.

4.5 DIAGNOSTICS AND MEASUREMENTS

To monitor the transport of the electron beam along modules 3 and 4, a variety of diagnostic elements are used. These include current monitors (toroids) and position monitors.

As well, for commissioning and setting up the transfer line, the beam will be allowed to proceed directly to beam dumps where the beam current can also be measured.

4.5.1 Current Monitors

An integrating current transformer (ICT) is located just before OP2 and at the beginning of module 3. Another ICT is located near the end of module 4. The ICTs measure the total charge in the beam pulse train.

4.5.2 Transition Radiation Monitors

After OP2, four (4) transition radiation monitors⁵ (TRM) will be used to precisely measure the size of the electron beam and beam position along the transfer line. An additional TR monitor will be used to measure the beam profile after the straight through port of the first 30 degree dipole (B0108-02).

4.5.3 Spill Monitors

Beam spill monitors⁶ will be used at several locations along the transfer line to detect beam spills that could indicate mis-steering or poor focusing.

4.5.4 Temperature Monitors

Thermocouples will be used to monitor the temperature of the magnet coils.

4.5.5 Energy Measurement

Since the beam energy along modules 3 and 4 remains constant, no energy measurement is required.

4.5.6 Beam Function Measurements

Beam functions at the end of module 4 (booster injection entrance) will be made as described in reference 1.

5.0 COMMISSIONING PLAN

ATTENTION: Before the beam can be transported through the first 21 degree dipole (B0004-01), the second 21 degree dipole (B0108-01) must be set at an equal but opposite field value. This will ensure that the beam will not exit straight through the second dipole but continue horizontally in the transfer tunnel.

Similarly, before the beam can be transported through the first 30 degree dipole (B0108-02) the second 30 degree dipole (B1300-01) must be set at an equal but opposite field value. This will ensure that the beam will not exit straight through the second dipole but continue horizontally in the booster tunnel.

Commissioning of the LTB brings the electron beam into the booster tunnel for the first time. Transportation of beam into this area requires the radiation levels to be monitored by the Health Safety and Environment (HSE) manager or designate as discussed in the safety report⁷.

5.1 MODULE 3

Initially the dipoles (B0004-01 and B0108-01) are set to the beam energy determined by the ESS (see reference 1) using the standard dipole setting procedure. The quadrupole triplet (QD0004-02, QF0004-02 and QD0004-03) is set to the theoretical values¹ as determined from the beam energy. The values of the dipoles are then empirically fine-tuned by oscillating the center quadrupole (QF0004-02) and removing the vertical steering using B0004-01. The quadrupole doublet (QD0108-01 and QF0108-0) is adjusted to minimize the beam size as observed on TRM0108-02 at OP3. **For personnel protection, radiation will be monitored as described in the Safety Report⁷. For this purpose, the beam current should start at a small value and should only be raised to the design value with the permission of the Health Safety and Environment (HSE) Manager.**

5.1.1 Steering

Steering through module 3 is adjusted with three (3) sets of steering coils. Also, as mentioned, the dipole magnets may have to be adjusted by small amounts.

For machine protection, radiation levels will be monitored by three (3) beam spill monitors (BBLM0004-01, BBLM0108-01 and -02).

The position of the beam in the vertical transport is optimized by using both the horizontal and vertical components of steering magnet ST0004-02 and observing the beam with TRM0108-01 and -02. The QF quadrupole is oscillated and steering removed using the horizontal steering magnet. The QD magnets in the quadrupole triplet are oscillated and steering removed using the vertical steering magnet.

Similarly, steering is removed in the following quadrupole doublet using steering magnet ST0004-03. (Again, oscillate QF for horizontal steering and QD for vertical steering.) At this point the beam should appear centered on both the position monitors (TRM0108-01 and SLM0108-01) that are immediately after the doublet. Finally, steering magnet ST0108-01 is used to center the beam on TRM0108-02 at OP3.

Properly focused, the beam is now ready for transport through module 4.

5.1.2 Current Measurement

The current at the end of module 3 can be measured using the beam dump straight beyond OP3 (BST0108-01). For this purpose, dipole B0108-02 should be degaussed and set to 0 field. To focus the beam on the dump, quadrupole QB0108-01 can be used. Steering magnet ST0108-02 can be used here as well. Current measurements should confirm a transport efficiency of near 100% through module 3.

5.2 MODULE 4 (to BST1300-01)

Initially the dipoles (B0108-02 and B1300-01) are set to the beam energy determined by the ESS, using the standard setting procedure. Quadrupole QB0108-01 and the quadrupole triplet (QD0108-02, QF0108-02, QD-0108-03), the quadrupole doublet (QD1300-01 and QF1300-01) and the bipolar quadrupole (QB1300-01) are set to the theoretical values¹ as determined from the beam energy. The values of the dipoles are then empirically fine-tuned by oscillating the center quadrupole (QF0180-02) and removing the steering. After transport through this section, the beam is on the plane of the booster. **For personnel protection, radiation will be monitored as described in the Safety Report. For this purpose, the beam current should start at a small value and should only be raised to the design value with the permission of the HSE Manager.**

5.2.1 Steering

Steering through the first section of module 4 is adjusted with three (3) sets of steering coils. As mentioned, the dipole magnets may have to be adjusted by small amounts. For machine protection, radiation levels will be monitored by three (3) beam spill monitors (BBLM0108-03, BBLM0108-04 and BBLM1300-01).

The position of the beam in the vertical transport is optimized by using steering magnets ST0108-02 and ST0108-03 and observing the beam with TRM1300-01. The QF quadrupole is oscillated and steering removed using the horizontal steering magnets. The QD magnets in the quadrupole triplet are oscillated and steering removed using the vertical steering magnets and dipole B0108-01.

Steering in the doublet and bipolar quadrupole following dipole B1300-01 cannot be removed until the second part of module 4 is set up.

5.2.2 Current Measurement

The current after dipole B1300-01 can be measured using the beam dump (BST1300-01) straight beyond dipole B1300-02. For this purpose dipole B1300-02 should be degaussed and set to 0 field. To focus the beam on the dump, the quadrupole triplet in front of the dipole can be used. Steering magnet ST1300-01 can be used here as well. Current measurements should confirm a transport efficiency of near 100% through this section of module 4.

5.3 MODULE 4 (B1300-02 to BOOSTER INJECTION)

Initially the dipoles (B1300-02 and B1300-02) are set to the beam energy determined by the ESS, using the standard setting procedure. Quadrupoles (QF1300-02 and QB1300-02) are set to the theoretical values¹ as determined from the beam energy. The values of the dipoles are then empirically fine-tuned by oscillating the quadrupole (QF1300-02) and removing the steering. After transport through this section the beam is bent toward the booster injection septum. This final “achromat” is the most critical for proper beam matching to the booster. **To protect the booster injection septum the inline beam stop (BST1300-02) must be in place. For personnel protection radiation will be monitored as described in the Safety Report. For this purpose the beam current should start at a small value and should only be raised to the design value with the permission of the HSE Manager.**

5.3.1 Steering

Steering through the remainder the first section of module 4 (see sec. 5.2) and the second section of module 4 is adjusted with three (3) sets of steering coils. For machine protection, radiation levels will be monitored by three (3) beam spill monitors (BBLM1300-01, BBLM1301-01 and BBLM1301-02).

The position of the beam in the last three quadrupoles of the previous section (QD1300-01, QF1300-01 and QB1300-01) is optimized by using steering magnets ST1300-01 and ST1300-02 and observing the beam with TRM1300-02. The QF quadrupole is oscillated and steering removed using the horizontal steering magnets. The QD quadrupole or the QB quadrupole (with a positive value) is oscillated and steering removed using the vertical steering magnets.

The position of the beam in the 85 degree achromat is also optimized by using steering magnets ST1300-01 and ST1300-02 and observing the beam with

TRM1300-02. Quadrupole QF1300-02 is oscillated and steering removed using the dipole B1300-02. Some adjustment to B1300-03 may also be required. For the vertical steering, quadrupole QB1300-02 is oscillated (with a negative value) and steering removed using both vertical steering magnets. At this time the steering in QD1300-01 should be rechecked since ST1300-01 will have been used.

Finally, steering magnets ST1300-02 and ST1300-03 are used to position the beam at TR1300-03 located at the entrance to the booster injection septum.

5.3.2 Current Measurement

The current at the booster injection septum can be measured using the in-line beam dump BST1300-02, as well as the current transformer ICT1300-01. Current measurements should confirm a transport efficiency of near 100% through this section of Module 4. Note: Although 100% efficiency is probable for the LTB line, a 10% loss has been allowed for in beam loss estimates⁸. Therefore, it is acceptable that the current measured here is 90% of the current measured at the end of the linac.

5.4 BEAM PARAMETERS

5.4.1 Beam Functions

Beam parameters at the booster injection septum are measured as described in references 3 and 4. At the entrance of the booster injection septum, these functions are: $\beta_x = 2.93$ m, $\alpha_x = 1.41$, $\beta_y = 13.94$ m, $\alpha_y = -2.53$, $\eta_x = 0.26$ m, $\eta_x' = -0.05$, $\eta_y = 0$ m and $\eta_y' = 0$. Since the energy spread of the injected beam is expected to be small, the requirement to match the η functions can be relaxed and these functions can be ignored.

The matching of the other four functions is achieved by using three single quadrupoles (QD1300-01, QF1300-01 and QF1300-02) and one set of quadrupoles (QB1300-01 and QB1300-02) which are controlled to be at equal but opposite values.

The beam functions are measured as described in Appendix C of reference 3. The measurement involves using the quadrupoles described in the above paragraph and the beam position/profile monitor (TRM1300-03) near the booster injection septum. To match the beam to booster machine functions, adjustments are made as described in section 6 of reference 3. Further refinements are described in reference 4. At this time, the beam functions should be adjusted to the theoretical values of the booster machine functions. Once the actual booster machine functions are measured the injected beam can be further refined.

5.4.2 Beam Emittance

Both the horizontal and vertical emittances are measured as described in reference 3. The beam emittances will have been measured in Phase I of the commissioning. To check the emittance at the booster injection septum, quadrupole QB1300-02 and position/profile monitors TRM1300-02 and TRM1300-03 can be used as an emittance monitor.

6.0 MACHINE PROTECTION

To avoid excessive beam spills along the LTB, the machine protection system must be enabled before the line can be operated. Systems that are continuously monitored include temperature control, power supply statuses and radiation levels.

6.1 VACUUM FAILURE

The vacuum in the beam pipe, during the course of operations, must be lower than a predetermined value before beam is allowed to pass through. If this value is exceeded the gun will be automatically turned off.

6.2 TEMPERATURE CONTROL

Temperature of the magnet coils will be monitored to ensure reliable operation of the magnets. Cooling channels blocked by debris can cause the temperature to increase. A shorted coil could cause the temperature to decrease. In the case the coil temperature is outside established "normal" values, the gun will be turned off at the operator's discretion and the magnet in question will be checked by maintenance staff.

6.3 POWER SUPPLIES

Power supply failures may result in the mis-steering or defocusing of the beam in the LTB. Consequently, the failure of any magnet power supply, or a sudden variation in voltage drop across a magnet, will result in the gun being turned off.

6.4 RADIATION MONITORING

Beam loss monitors at various locations in the LTB vault will indicate abnormal levels of radiation. "Normal" levels of radiation will be established as discussed below. Monitoring of radiation levels can indicate problems with the beam steering that may result in excessive radiation at specific sites. Disabling of the machine will be at the discretion of the machine operator.

If radiation levels exceed safe working conditions outside the vault, the linac will automatically be disabled. Part of the commissioning process will be to establish the correlation between radiation levels inside the vault with those external to the vault, where safe working conditions must be maintained.

7.0 PERSONNEL PROTECTION

Operation of the linac (and the LTB) cannot proceed until the Access Control Interlock system is enabled. Its primary purpose is to ensure that personnel are not exposed to unacceptable levels of radiation. A secondary function is to ensure that personnel are not exposed to conventional hazards such as electrical and chemical hazards.

For these reasons, the linac and transfer line is enclosed in a secure area. No personal are allowed in the secure area during operation of the machine. This is ensured by a lockup procedure as described in reference 9. Once the lockup is complete the electron gun can be enabled.

7.1 RADIATION SAFETY

During commissioning and routine operation of the transfer line, radiation levels both inside and outside the transfer line vault will be monitored.

Radiation levels in areas outside the vault will be monitored to ensure that radiation levels are in compliance with the guidelines described in the safety report⁷.

Radiation levels inside the vault will be monitored to indicate possible errant beam conditions during commissioning or setup and to establish “normal” background levels during routine operation. Radiation surveys also serve to indicate levels of residual radiation after the linac is turned off before routine access to the secure area is allowed. Re-entry will be permitted once the radiation levels are deemed safe. At re-entry, personal dosimeters and hand held radiation survey meters will be used to monitor doses received and monitor for residual radiation levels in the vault. Once radiation levels are established, access to different areas can be determined and regulated.

7.1.1 Commissioning Considerations

7.1.1.1 Radiation Outside the Vault

Radiation levels outside the LTB vault will be measured at each stage of commissioning. If levels exceed acceptable levels⁷, commissioning will proceed with the gun current reduced to bring the radiation levels to an acceptable level.

7.1.1.2 Radiation Inside the LTB Vault

Each time the linac is turned off, residual radiation levels inside the LTB vault will be measured by radiation safety personnel and safe working conditions established. All personnel entering the vault area are required to wear personal Thermo Luminescent Dosimeters (TLDs).

Short term access to the LTB vault will be done with a so-called “button access” as described in the lock-up procedure⁹. One person at a single access point will ensure that personnel entering the linac vault will carry radiation monitoring

equipment and personal dosimeters. Button access is possible only when the beam is off.

BOOSTER and BTS (to BTS dump)

8.0 PURPOSE

This section of the report describes the principal components of the booster and the actions required to commission the booster to meet its requirements as the third stage of the injection system of the Canadian Light Source. As well, part of the Booster-To-Storage ring transfer line (BTS) will be described.

Requirements are to inject a pulse train of electrons from 2 to 136 ns in duration with a beam energy of 200 to 250 MeV and an average beam current, in the pulse train, up to 60 mA. The electrons are then accelerated to an energy of 2.9 GeV and extracted from the booster for transfer to the CLS storage ring.

At injection, the beam will have horizontal and vertical emittances not exceeding 0.3 mm-mrad and an energy spread of 0.15% or less. The pulse train contains bunches of electrons at a frequency of 2856 MHz. The phase spread in each bunch is about 120 degrees. At the injection point of the booster, the beam functions should be matched to the machine functions of the booster ring. At the entrance of the booster injection septum these functions are: $\beta_x = 2.93$ m, $\alpha_x = 1.41$, $\beta_y = 13.94$ m, $\alpha_y = -2.53$, $\eta_x = 0.26$ m, $\eta_x' = -0.05$, $\eta_y = 0$ m and $\eta_y' = 0$.

Before an attempt to accelerate the beam is made, the beam will be stored at the injection energy (nominally 250 MeV). This can proceed first with the booster RF system OFF and then with the RF system ON. With the RF system ON, the beam should store long enough to enable measurement of machine parameters and adjustment of the closed orbit.

Once the measurements and adjustments are made at the injection energy, the beam can be accelerated to the design energy of 2.9 GeV. Machine parameters at various energies during the acceleration process can be measured “on the fly”. Adjustments to the ramping curves of the dipole magnets, quadrupole magnets and steering magnets will be made at this time. RF ramping will also be adjusted to minimize beam losses.

At the maximum energy (nominally 2.9 GeV) the beam can be extracted. The extracted beam will proceed down the BTS to the BTS beam dump located after the straight through port of the first BTS dipole.

This report also describes the requirements for safely commissioning and operating the Booster and the first part of the BTS. Due to the levels of radiation produced by possibly mis-steered beams during injection, acceleration and extraction the booster is enclosed in a tunnel. The part of the BTS that will be used in Phase II commissioning is also enclosed in the booster tunnel, with the exception of the BTS beam dump which is located in the storage ring tunnel. The tunnels serve to exclude access to booster and storage ring environments while the booster is in operation and to shield the environment external to the tunnels from the radiation that is produced. As well, access to these secure areas must be restricted until the residual levels of radiation have been measured and safe working conditions have been established.

9.0 BACKGROUND

The purpose of this section of the report is to provide an overview for the commissioning and operational procedures of the booster and BTS required to safely and efficiently inject, accelerate and extract a beam from the CLS booster. The booster and BTS are composed of many components that have to be tested and deemed ready for the commissioning process. Details of these components are found in the references provided throughout the report.

The report includes all aspects of operation from the booster injection point to the beam dump of the BTS. Thus, all the components required to inject, accelerate and extract a beam from the CLS booster are described.

10.0 EQUIPMENT REQUIRED

10.1 BOOSTER

The booster is described in detail in references 10 and 11. The primary components are 20 dipole magnets, 28 quadrupole magnets and two five-cell RF cavity. The 28 quadrupole magnets form a lattice with 14 FODO cells. Each cell has one “F” quadrupole and one “D” quadrupole. For total symmetry there would be two dipoles per cell that would give a total of 28 dipoles. Eight dipoles are removed, however, and each replaced with a straight drift section (leaving 20 dipoles). These straights are used for the injection and extraction septa, kickers and the RF cavities. All these elements are ramped together to accelerate the beam from (nominally) 250 MeV to (nominally) 2.9 GeV.

The dipole magnets are powered in four groups of five with four identical power supplies. The groups are group 1: B1302-01 to B1302-05; group 2: B1302-06 to B1302-09 and B1303-01; group 3: B1304-01 to B1304-05; and group 4: B1304-06 to B1304-10.

The quadrupoles are powered in two families of 14 quadrupoles. The families are family 1: QD1301-01, QD1302-01 to QD1302-05, QD1303-01 and QD1303-02, QD1304-01 to QD1304-06; and family 2: QF1302-01 to QF1302-06, QF1303-01, and 04-01 to QF1304-07.

For injection there is an injection septum (B1300-01) and one injection kicker (K1301-01). For extraction there is an extraction septum (B1303-02), an extraction kicker (K1303-01) and 3 “bump” magnets (BMP1303-01, BMP1303-02 and BMP1303-03). Secondary components are orbit correction magnets and a variety of diagnostic elements.

10.2 BTS TRANSFER

The portion of the BTS transfer line¹² required for Phase II commissioning includes a quadrupole magnet, two sets of steering magnets and a number of diagnostic elements. This short portion of the BTS transfer line brings the beam to a final beam dump.

10.3 TIMING SYSTEM

Timing signals are required for both injection and extraction. At injection, both the injection septum and the injection kicker must be fired at the appropriate time to efficiently inject the beam into the booster. At extraction, timing signals must be supplied to the extraction bump magnets, the extraction kicker and the extraction septum. Details of the timing system are given in reference 13. Timing signals will also be used to gate the diagnostic electronics.

10.4 ORBIT CORRECTION AND STEERING

The orbit of the beam in the booster is corrected by 14 horizontal and 8 vertical corrector magnets. The magnets can be used to keep the deviations from the ideal orbit small, as well as to correctly position the beam for efficient injection and extraction. Special orbit correctors called bump magnets are used to move the beam closer to the extraction septum during the extraction process.

Steering magnets are also used in the BTS transfer line to enable efficient beam transport.

10.5 DIAGNOSTICS AND MEASUREMENTS

To monitor the orbit and characterize the quality of the electron beam in the booster, a variety of diagnostic elements are used. These include current monitors and position monitors.

For setting up the BTS transfer line, the beam will be allowed to proceed directly to a beam dump where the beam current can also be measured.

Also, a variety of beam loss monitors will be used in both the booster and the BTS transfer line.

10.5.1 Current Monitors

Fast current transformers (FCTs) are located at two locations in the booster. The first (FCT1301-01) is just after the injection septum. The second (FCT1304-01) is located on the other side of the booster.

10.5.2 Strip-line Monitors

Two strip-line monitors (SLM) are located in the booster. Both are located in the fourth quadrant of the booster. The first (SLM1304-01) will be used to excite the beam to create betatron oscillations. The second (SLC1304-2) is located just upstream of the injection septum and will be used to measure the position of the beam at the end of each turn and, in the beam storage mode, will be used to measure the beam tunes by measuring the betatron oscillations.

10.5.3 Synchrotron Light Monitors

Two booster dipole magnets will be equipped with synchrotron light monitors. These monitors can be used to measure the tune of the beam during the ramping process.

10.5.4 Spill Monitors

Beam spill monitors will be used at several locations around the booster to detect beam spills that could indicate mis-steering or poor focusing.

10.5.5 Temperature Monitors

Thermocouples will be used to monitor the temperature of the magnet coils.

11.0 COMMISSIONING PLAN

(For the purposes of this report, the injection energy is nominally take to be 0.250 GeV (250 MeV). In reality, the injection energy may vary between 0.20 and 0.25 GeV.)

The first stages of commissioning (injecting and storing without ramping) involves beam energies that are familiar from previous commissioning of the linac and LTB. Radiation levels must be monitored as the beam enters new areas of the booster tunnel.

ATTENTION: Once ramping of the beam energy commences, power levels associated with the beam increase linearly with beam energy. At full energy (2.9 GeV), a 9% beam loss is equivalent to the loss of the entire beam at the injection energy (0.25 GeV).

The commissioning plan described below follows the commissioning plan supplied by Danfysik. Danfysik is building the booster¹¹ for CLS and will be participating in and supervising the commissioning process. The Danfysik commissioning plan is given in Appendix B.

11.1 INJECTION

Once the beam is centered in TRM1300-02 and TRM1300-03, and the beam machine functions are deemed satisfactory, the beam is ready for injection into the booster. The booster injection septum should be set to the nominal value for the beam energy. The standard setting procedure should be used. The booster dipoles should be set to the nominal beam energy. With the dipoles on and the booster quadrupoles off, any beam making it through the septum will be lost diffusely over many meters of the booster.

Once all the magnets are set, the inline beam stop (BST1300-02) can be withdrawn. The beam should be seen on the intercepting viewer (pop-up) just beyond the injection septum. As well, beam current should be measured in the FCT (FCT1301-01) following the septum. If no beam is observed, the injection

septum field should be slowly scanned until the beam is observed. Some adjustment to LTB correctors (ST1300-02 and -03) may also be required. The timing of the septum excitation pulse can also be adjusted to optimize the current in the FCT. The beam loss monitors in the vicinity of the injection septum can also be used to optimize the injection process. Current measurements in the FCT should confirm 80% or greater electron beam transmission through the injection septum. Once the injection efficiency is satisfactory, the booster commissioning can proceed.

Until the efficiency is satisfactory, the HSE manager must approve of operations with low injection efficiency. Commissioning may proceed if the radiation levels outside the booster tunnel are sufficiently low. If required, this can be achieved by operating at low average beam currents and/or low repetition rates.

11.1.1 Steering

As mentioned above, steering through the septum is accomplished through a combination of scanning the injection septum and using both the horizontal and vertical channels of the LTB steerers ST1300-02 and -03.

11.1.2 Current Measurement

The current transmitted through the septum is measured with the current transformer (FCT1301-01) following the injection septum. This should be compared with the current previously measured at the intercepting beam stop (BST1300-02) or more directly with the current transformer ICT1300-01.

11.1.3 Timing

The timing signal for the injection septum is adjusted to optimize the beam transmission through the septum. Timing signals can also be used to trigger the FCT and the beam loss monitors.

11.1.4 Beam Loss Monitors

Two types of beam loss monitors⁶ are located at many locations around the booster. With two monitor types, both prompt and slow beam losses can be detected.

11.2 FIRST TURN

Once the injection is optimized, the beam is ready to be tracked once around the booster. For this purpose, the dipole magnets should be at their nominal value as described above. The two families of booster quadrupole magnets should now be set to their nominal values for the beam energy. The orbit corrector magnets should be available and all set to zero strength.

Next the injection kicker must be activated. The kicker value should be set to the nominal value determined by the beam energy. The kicker timing must be

adjusted so that the beam is injected when the kicker is at its maximum “flat-top” value and the end of the pulse train arrives when the kicker amplitude begins to fall. The kicker amplitude is adjusted to kick the beam onto the booster axis. The horizontal orbit correctors and the vertical orbit correctors are now adjusted so that the beam is seen on the intercepting beam viewers located after dipole B.17, dipole B.01 and dipole B.07 (Danfysik notation). When this is accomplished, in turn, the beam will be about three quarters of the way around the ring. Finally the beam is steered the remainder of the first turn where it can be observed with the stripline monitor (SLM1304-02) just upstream from the injection septum.

Since the first turn is done at the injection energy, radiation levels should not be too severe even if the beam is occasionally totally lost. Nevertheless, radiation levels will be monitored to ensure safe operating conditions. The radiation monitors should be helpful in steering the beam around the first turn.

11.2.1 Steering

Steering the beam around the first turn is accomplished with fourteen horizontal and eight vertical orbit correctors. The single turn produced by sequential use of the steering magnets will not necessarily produce a closed orbit.

11.2.2 Current measurement

The beam current can be measured using the current transformer following the injection septum (FCT1301-01) and a second transformer just before dipole B.03 (FCT1304-01). After one turn is completed, both the injected beam and the first turn should be observed in the first current transformer.

Successful completion of the first turn around the booster should result in near 100% transmission of the beam current.

11.2.3 Focusing

Focusing of the beam is accomplished with two families of quadrupoles. The first family (QFs) is horizontally focusing and the second family (QDs) is vertically focusing. Although these quadrupoles will be set to the nominal value determined by the beam energy, small adjustment may aid in transporting the beam around the first turn.

11.2.4 Timing

The timing of the injection kicker will have been adjusted during injection. Once the beam has made it around one turn, the timing can be checked to ensure that the kicker amplitude is zero when the head of the pulse train reaches the end of the first turn.

11.2.5 Beam Loss Monitors

A large number of beam loss monitors around the booster will aid in tracking the beam around the first turn. Two types of monitors are available. These are described in reference 6.

11.3 LOW ENERGY STORAGE (NO RF)

After the first turn is successfully accomplished, the beam orbit can be adjusted to allow the beam to store for many turns. This will first be attempted with no RF power supplied to the cavities. Under these conditions, it should still be possible to store the beam for many thousands of turns. (At 250 MeV, the beam will lose about 0.02% of its energy in 10,000 turns.)

Since tracking the beam around the first turn does not necessarily produce a closed orbit, all the orbit correctors have to be adjusted to form a closed orbit. Successive passages of the beam can be observed on the stripline located upstream from the injection septum. The storage efficiency may be further optimized by adjusting the two quadrupole families. It may also be helpful to fine tune the four individual power supplies for the dipole magnets.

Radiation levels during this stage of operations will be similar to those produced during tracking around the first turn. The two types of beam loss monitors will be useful in identifying whether beam losses are prompt or occurring over time.

When the storage is optimized, the beam will be lost uniformly over tens of thousands of turns.

11.4 LOW ENERGY STORAGE (WITH RF ON)

Once the storage efficiency is optimized with no RF, the RF power will be turned on. With the RF on at least 50% of the injected beam should be stored for the entire time between injection pulses (one second). When the beam capture is optimized, the entire captured beam current should remain constant until the next injection occurs. At this time, the injection kicker will kick the stored beam out of the booster when the new pulse is being injected. The beam loss monitors will indicate a “spike” of activity at the time that the injection kicker fires.

The beam storage can be optimized by iterative adjusting the RF system, the beam orbit and the beam tunes.

11.4.1 RF System

To capture the beam at the nominal injection energy (250 MeV), the cavity voltages should be set to about 0.17 MV. Details of the RF system are given in the Danfysik Conceptual Design Report¹¹. At the time of commissioning, no beam chopper will be available. Since the 2856 MHz bunches from the linac are asynchronous with the 500 MHz RF of the booster, phasing of the booster RF is arbitrary. The capture efficiency will unlikely exceed 50%. It may be possible to increase the RF voltage and thus increase the capture efficiency. However, care

must be taken in increasing the RF voltage in order to avoid too large synchrotron oscillations.

11.4.2 Orbit Control

Once the beam is stored, the injection repetition rate should be reduced so that the beam has time to damp. At 250 MeV, the damping times are less than 4 seconds, so a repetition rate of 0.1 Hz would be useful. With a damped beam it will be possible to measure the position of the closed orbit using the BPMs. Once the beam positions are known, the orbit can be corrected using the global orbit correction scheme¹⁴.

11.4.3 Tuning

Once the beam is stored and damped, the tunes can be measured using the two striplines. The first stripline is used to excite the beam while the second is used to measure the response. Tunes can be adjusted using the two families of quadrupoles. The optimum tune for the best storage efficiency may vary from the nominal tunes of (5).18 horizontal and (2).38 vertical. As indicated by the brackets, only the fractional part of the tune is measured.

11.5 RAMPING THE ENERGY

Ramping the beam energy will create radiation levels higher than previously encountered. Ramping should initially proceed at lower currents in the pulse train and/or at a lower repetition frequency. Radiation levels outside the booster tunnel will be closely monitored and area monitors adjusted so that the beam will automatically be turned off in the event that acceptable radiation levels are exceeded.

The beam energy is ramped by simultaneously increasing the fields in the dipoles, quadrupoles, orbit correctors and the RF cavities. The dipole, quadrupole and orbit corrector field strengths are increased using the same ramping profile. In this way, the relative field strengths in the magnets remains constant, resulting in constant tunes during the ramp. The RF voltage does not necessarily have to be ramped with the same ramping profile. The RF voltage will, however, stay approximately proportional to the magnet strengths.

11.5.1 Ramping to Intermediate Energies

It will be possible to ramp to intermediate energies and hold that energy long enough to make measurements on the beam orbit and the tunes. The maximum energy that can be stored is determined by the performance of the dipole power supplies. This value is around 1.0 GeV. At different energies up to this value, the closed orbit and the tunes can be optimized. Using the new optimum orbits and tunes will mean that the ramping profiles will no longer be identical for each magnet type. Also, for each stored energy the cavity voltages can be optimized and the RF ramp appropriately modified.

11.5.2 Ramping to Full Energy

Beyond 1.0 GeV, the ramping can continue to the desired final energy in a pulsed mode. Full energies ranging from 1.5 to 2.9 GeV will be required. At the higher energies where the beam cannot be stored, the beam positions and tunes will be measured “on the fly”. (Note: measuring the beam characteristics “on the fly” at low energies is also possible and storing the beam at lower energies may not be required.) Information on the beam position and tunes will be used to modify the ramping profiles for all the magnet types and the RF voltage.

During this stage of the commissioning, the beam will be lost or dumped by the injection kicker at the beginning of the next cycle. **This phase of the commissioning process is expected to generate higher levels of radiation.** For example, at 2.9 GeV the radiation levels will be over ten higher than the levels encountered while storing the beam at the injection energy. Using low currents and/or low repetition rates may be required. The expected radiation levels will be known by scaling from the low energy results.

During ramping, it is expected that over 55% of the beam will be lost (see reference 8). This includes the losses due to the fact that the 2856 MHz pulse train will not be chopped, and thus, the capture efficiency is reduced.

11.6 EXTRACTION

Extraction of the beam from the booster will require close monitoring of radiation levels in the area of the extraction septum. The beam will be directed toward the BTS beam dump located inside the booster tunnel. Radiation levels may indicate that extra shielding be required around the beam dump. Extraction should initially proceed with low average currents. Currents will be increased only with the permission of the HSE manager.

Once the beam is successfully ramped to the desired extraction energy and the closed orbit is corrected at the extraction energy, the extraction process can begin. Extraction of the beam involves “bumping” the beam and then kicking the beam into the extraction septum.

11.6.1 Timing

All elements of the extraction system must be triggered with the timing system. These elements are the bump magnets, the extraction kicker and the extraction septum. The beginning of the extraction sequence begins with the bump magnets. Once triggered, they require about 20 ms to reach full amplitude. After this time, the septum and the extraction kicker can be triggered.

11.6.2 Bumping

The first part of the extraction process is to “bump” the beam closer to the extraction septum using the three bumper magnets. The process is described in reference 11. The bumper magnets are orbit correctors that are used for the sole purpose of moving the beam toward the extraction septum. The bump

amplitudes should be adjusted to their nominal values for the desired extraction energy. The BPMs in the vicinity of the extraction septum will indicate if the desired bump is created. The bump can be fine tuned by adjusting the individual amplitudes of the bump magnets.

11.6.3 Extraction

Once the desired bump is established, the extraction process can begin. The extraction kicker and the extraction septum should be set to the desired extraction energy. This energy corresponds to a small flat top on the ramping profile for the dipole magnets (see reference 11). During this short period of constant energy, the extraction kicker and the extraction septum can be triggered. The kicker timing must be adjusted so that the kicker amplitude begins to rise just after the passage of the tail end of the beam pulse. The kicker should reach full amplitude before the head of the beam pulse reaches the kicker. The kicker rise time is less than 190 ns. The kicker amplitude and the extraction septum amplitude can also be finely adjusted.

With the proper adjustments, the beam pulse should be observed exiting the extraction septum into the BTS transfer line. The beam can be observed with a TRM just after the extraction septum. A short transport in the BTS transfer line will bring the beam to a current monitor. Efficient extraction will result in over 80% of the beam in the transfer line.

Radiation levels in the extraction septum may be high and local shielding will be employed if required. Once efficient extraction is established, the beam current can be increased to the desired current of 10 mA for the duration of the extracted beam pulse train.

11.6.4 Beam Optimization

Once the beam is efficiently injected, ramped and extracted, some time will be spent optimizing the processes. This will mainly involve fine tuning of the various elements. During this process, radiation levels should be observed to be within the levels outlined in the safety report.

11.7 BOOSTER TO STORAGE RING (BTS) TRANSPORT

The last part of Phase II commissioning involves a short transport of the beam down the first leg of the BTS transfer line. After exiting the extraction septum, the beam can be steered by a pair of steering magnets down the BTS line. The beam will go through at least one quadrupole* magnet and then onto a beam dump. If required, the beam dump will be adequately shielded so that it can contain the radiation created by dumping all the beam. At both the location of the quadrupole and in front of the beam dump there will be another TRM. As well, near the quadrupole there will be a FCT and an ICT (integrating current transformer). Currents measured in the transformers and the dump will be used to estimate the extraction efficiency. (* At the time of Phase II commissioning,

the BTS line may not be in its final configuration. One quadrupole is required for diagnostic purposes.)

11.7.1 Beam Emittance

The BTS quadrupole and the two BTS TRMs can be used to measure the emittance of the extracted beam, as described in reference 12.

12.0 MACHINE PROTECTION

To avoid excessive beam spills along the booster, the machine protection system must be enabled before the booster can be operated. Systems that are continuously monitored include temperature control, power supply statuses and radiation levels.

12.1 VACUUM FAILURE

The vacuum in the booster beam pipe must be lower than predetermined values before beam is allowed to pass through. Loss of vacuum quality automatically causes the gun to be turned off.

12.2 TEMPERATURE CONTROL

Temperature of the magnet coils will be monitored to ensure reliable operation of the magnets.

12.3 POWER SUPPLIES

Power supply failures may result in the mis-steering or defocusing of the beam in the booster. Consequently, the failure of any magnet power supply, or a sudden variation in voltage drop across a magnet, will result in the gun being turned off.

12.4 RADIATION MONITORING

Beam loss monitors at various locations in the booster vault will indicate levels of radiation. Monitoring of radiation levels can indicate problems with the beam steering that may result in excessive radiation at specific sites. Disabling of the machine will be at the discretion of the machine operator.

If radiation levels exceed safe working conditions outside the booster tunnel, the gun will automatically be disabled. Part of the commissioning process will be to establish the correlation between radiation levels inside the vault with those external to the vault, where safe working conditions must be maintained.

As well, components may become radioactive, which will make their maintenance more difficult.

13.0 PERSONNEL PROTECTION

Operation of the booster (and the BTS) cannot proceed until the Access Interlock system is enabled. Its primary purpose is to ensure that personnel are not exposed to unacceptable levels of radiation. A secondary function is to ensure that personnel are not exposed to conventional hazards such as electrical and chemical hazards.

For these reasons, the booster and BTS transfer line are enclosed in a secure area. No personnel are allowed in the secure area during operation of the booster and transfer line. This is ensured by a lockup procedure as described in reference 15. Once the lockup is complete, the booster can be enabled.

13.1 RADIATION SAFETY

During commissioning and routine operation of the transfer line, radiation levels both inside and outside the booster tunnel will be monitored.

Radiation levels in any area outside the tunnel will be monitored while the beam is on to ensure that radiation levels are in compliance with the guidelines described in reference 7.

Radiation levels inside the vault will be monitored to indicate possible errant beam conditions during commissioning or setup and to establish “normal” background levels during routine operation. Radiation surveys also serve to indicate levels of residual radiation after the booster is turned off, before routine access to the secure area is allowed. Re-entry will be permitted once the radiation levels are deemed safe. At re-entry, extra monitors such as personal dosimeters and hand held survey meters will be used to monitor doses received and check the background radiation levels. Once radiation levels are established, access times to different areas can be determined and regulated.

13.1.1 Commissioning Considerations

13.1.1.1 *Radiation Outside the Tunnel*

Radiation levels outside the booster tunnel will be measured at each stage of commissioning. If levels exceed acceptable levels⁷, commissioning will proceed with the gun current reduced to bring the radiation levels to an acceptable level.

13.1.1.2 *Radiation Inside the Booster tunnel*

Each time access to the booster tunnel is required, residual radiation levels inside the tunnel will be surveyed by radiation safety personnel to ensure safe working conditions. All personnel entering the vault area are required to wear TLDs.

Short term access to the booster vault will be done with a so-called “button access” as described in the lock-up procedure¹⁵. One person at a single access point will ensure that personnel entering the booster tunnel will carry radiation

monitoring equipment and personal dosimeters. Button access is possible only when the gun is turned off.

14.0 REFERENCES

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- 13] J. M. Vogt, "CLS Design Specification Timing System", CLS Design Specification 7.4.39.2 Rev. 2, January 30, 2000

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- 14] see for example: L. O. Dallin, "CLS Lattice Performance Analyses", CLS Technical Design Note 8.2.69.1 Rev. 0, November 27, 2000
 - 15] Booster Lock-up, (under preparation)

Appendix A: Diagrams and Drawings

LTB:

The LTB (from OP2) is shown in the following drawings:

LTB1/ME/0034407G, 408G, 409G

LTB1/ME/0034603G, 604G, 605H

The equipment necessary for the commissioning of the LTB is identified in the process flow diagrams (PFDs) for the following systems:

OPTICS: LTB1/PFD/OPT/0057201A, 202A

VACUUM: LTB1/PFD/VAC/0057211A, 212A

WATER: LTB1/PFD/PPG/WTR/0057221A, 222A

PNEUMATIC: LTB1/PFD/PPG/PNU/0057231A, 232A

BOOSTER:

The booster layout is shown in the following Danfysik drawing:

Booster Layout: 11691-050-C

Many detailed Danfysik drawings are also available (see reference 11).

The equipment necessary for the commissioning of the booster is identified in the PFDs for the following systems:

OPTICS: BR1/PFD/OPT/0057301A

VACUUM: BR1/PFD/VAC/0057311A

WATER: BR1/PFD/PPG/WTR/0057321A

PNEUMATIC: BR1/PFD/PPG/PNU/0057331A

RF: (in progress)

BTS:

The BTS layout is shown in the following drawing:

BTS 1/ME/0034800K

The equipment necessary for the commissioning of the BTS is identified in the PFDs for the following systems:

OPTICS: BTS1/PFD/OPT/0057401A

VACUUM: BTS1/PFD/VAC/0057411A

WATER: BTS1/PFD/PPG/WTR/0057421A

PNEUMATIC: BTS1/PFD/PPG/PNU/0057431A

Appendix B: Danfysik Commissioning Plan

Detailed plan for the commissioning of the CLS booster synchrotron

General remarks:

1. The indicated duration of each task below is only an approximate estimate of the expected time needed to complete the task. A more accurate estimation of the time consumption of each task is not possible because the commissioning to a large extent is about identifying and curing unforeseen problems.
2. Each task below is allocated extra time for unforeseen problems. It is the goal that this time in average equals the actual time required for identifying and solving the unexpected problems.
3. In presence of major unforeseen problems, it is often possible to jump to the next task in the commissioning plan while the problem is solved. This will speed up the commissioning.
4. It is assumed that the pre-injector linac is operating according to specifications and that the hardware of the booster synchrotron is brought into operation.
5. The time plan for the commissioning does not include delays resulting from insufficient infra structure at the site (power, water etc).

Storage of a beam at 250 MeV:

1. Check of the polarity of all magnetic elements (1 day).
2. Transport of the beam through the injection septum magnet (1 day).

First, the beam is positioned at the entrance of the septum channel utilizing the beam viewer shortly upstream of the septum magnet. Subsequently, the excitation of the septum magnet is scanned until the beam is observed at the beam viewer at the exit of the septum channel (possibly the correctors in the injection transfer line have to be adjusted as well). In addition the timing of the excitation pulse of the septum magnet is optimized.
3. Transport of the beam one revolution in the booster synchrotron (4 days).

The passage of the beam can be detected by the beam viewers, the button pickups, the striplines, and the beam loss monitors. Utilizing those diagnostic tools, the beam is transported once around the booster synchrotron by adjusting the excitation of the injection kicker magnet, the dipole magnets, the quadrupole magnets, and the corrector magnets.

4. Storage of the beam in the booster synchrotron (4 days).

With the stripline signal each beam passage can be observed. Adjusting the excitation of the injection kicker magnet, the dipole magnets, the quadrupole magnets, and the corrector magnets for the maximum number of turns, the beam is stored in the booster synchrotron. The beam will, however, be lost within a few milliseconds due to synchrotron light losses.

5. Start up of the RF system (2 days).

Start up and optimization of the RF system for an efficient capture of the electrons in the longitudinal bucket. The excitation of the dipole magnets has to be adjusted to match the revolution frequency with the RF frequency. In addition, the chopper of the pre-injector linac has to be synchronized with the RF system. Finally, tune measurements will be performed in order to check the position of the working point.

6. Correction of closed orbit deviation (4 days).

If required, the closed orbit deviation is corrected with the help of the corrector magnets.

7. Optimization of fast RF feedback loop (2 days).

The fast RF feedback loop will be optimized for an efficient reduction of the beam induced voltage in the accelerating structures.

8. General optimization of the stored beam current (5 days).

Beam acceleration:

1. Start of ramping of the dipole and quadrupole magnets to full excitation (1 day).

The shape of the quadrupole magnet ramps with respect to the dipole magnet ramp is determined from the field mapping of the magnets in order to ensure constant transverse tunes throughout the ramp.

2. Correction of the quadrupole magnet ramp (2 days).

If measurements of the transverse tunes reveal an unacceptable tune shift or beam loss occur during ramping, the ramping curve of the quadrupoles should be adjusted manually.

3. Correction of closed orbit deviation (2 days).

If required, the ramping curves of the corrector magnets are adjusted in order to reduce the closed orbit deviation throughout the ramp.

4. Out-gassing of vacuum chamber (10 days).

If the RF system has a vacuum interlock during ramping due to the intense emission of synchrotron light at high beam energy, the beam current will be reduced until the booster synchrotron is able to ramp to full energy. Subsequently, the beam current can gradually be increased as the vacuum chamber is cleaned by the synchrotron light.

5. Optimization of the ramping curves throughout the whole ramp (5 days). Optimization of the shape of the ramping curves for the maximum beam current at full energy.

Extraction process:

1. Bumping of the beam close to the extraction septum (1 day).

The beam is bumped towards the extraction septum until the tail of the beam is observed at the beam viewer at the extraction septum (the beam viewer is in the position in which its edge extends 2 mm beyond the septum blade).

2. Optimization of the extraction kicker (1 day).

Turning on the extraction kicker, the beam is kicked to the outside of the septum blade. The excitation and timing of the extraction kicker is adjusted until the beam is observed in the centre of the beam viewer in front of the extraction septum channel.

3. Transport of the beam through the extraction septum magnet (2 days).

The excitation and timing of the extraction septum magnet is adjusted until the beam is observed at the beam viewer following the septum magnet. If necessary, the excitation of the extraction kicker and the bumper magnets are optimized as well.

4. Optimization of the extraction process (5 days).

All extraction parameters are optimized for an extracted electron pulse with the maximum beam current and pulse length.

Verification of lattice parameters:

1. Transverse tunes (1 day).

The transverse tunes of the booster synchrotron are determined by recording the frequency spectrum of a stripline signal (preferable a difference signal in order to distinguish between the horizontal and the vertical plane) by a spectrum analyzer while the betatron oscillation of the beam is excited by the other stripline unit. During the measurement, the excitation frequency is produced by a swept-frequency generator which is synchronized with spectrum analyzer.

2. Chromaticities (1 day).

The chromaticity is determined by measuring the tune variation as a function of the RF frequency.

3. Momentum compaction factor (1 day).

The momentum compaction factor can be determined at the injection energy by measuring the revolution frequency as a function of the excitation of the bending magnets with the RF system turned off. The measurement should be performed within the first few milliseconds after injection in order to avoid synchrotron radiation-induced energy loss.

4. Closed orbit deviation (1 day).

The transverse position of the beam in the booster synchrotron is determined by means of the button pickups. The response of a BPM unit (4 buttons) to the transverse beam position will be calibrated before the installation.

5. Transmission loss.

Characterization of transmission loss from entrance of injection septum to the exit of the extraction septum.

Determination of beam properties:

1. Circulating beam current at 2.9 GeV (0 days).

The beam current is determined by means of the dc current transformer.

2. Transverse emittances of the circulating beam at 2.9 GeV (1 day).

The transverse emittances can be determined by recording the emitted synchrotron light in the bending magnets.

3. Momentum spread of the circulating beam at 2.9 GeV (1 day).

The momentum spread can be inferred from the frequency spectrum of the sum signal of the striplines since the momentum spread is related to the relative strength of the harmonics of the RF frequency in the frequency spectrum.

3. Beam current of extracted electron pulse at 2.9 GeV (0 days).

The beam current of the extracted electron pulse is determined by means of the fast current transformer in the extraction transfer line.

4. Pulse length of extracted electron pulse (0 days).

The pulse length of the extracted electron pulse is determined by means of the fast current transformer in the extraction transfer line.

5. Transverse emittances and momentum spread of the extracted beam (1 day).

These beam properties can be established by performing at least two quadrupole scans in the extraction beam line in which the beam profile is measured as a function of the excitation of an upstream quadrupole magnet.