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UNDER A CONTRIBUTION FROM THE
NATIONAL RESEARCH COUNCIL OF CANADA

OCTOBER 2002

The contributions on individual experiments in this report are outlines intended to demonstrate the extent of scientific activity at TRIUMF during the past year. The outlines are not publications and often contain preliminary results not intended, or not yet ready, for publication. Material from these reports should not be reproduced or quoted without permission from the authors.

CERN COLLABORATION

INTRODUCTION

This is the seventh year of the collaboration between TRIUMF and CERN which is producing accelerator components for the Large Hadron Collider (LHC) project. Three technical projects and two beam dynamics studies are presently being carried out. Twenty-four tasks have been successfully completed. The total funding for this work over the two Five-Year Plans (2000–2010) is $40.5 million, of which $11 million is for TRIUMF salaries and the remainder is for equipment and outside contract costs.

The largest contribution, in terms of dollars, is for the production of 52 special magnets for the two beam cleaning insertions in the LHC. These twin aperture quadrupoles are warm or copper coil magnets to permit operation with the anticipated beam losses in this region where the beam is carefully collimated to avoid beam losses in the superconducting magnets in the rest of the ring. In 1999, ALSTOM Canada (Tracy, Quebec) was awarded the contract for the production of the first 17 of the twin aperture quadrupole magnets. ALSTOM had previously built a prototype magnet which did not meet the magnetic field requirements, so changes to the lamination design and assembly tooling were required. The first series magnet was delivered to CERN in March of this year, after satisfying the required assembly tolerances at the factory. Magnetic field measurements on this magnet carried out at CERN proved the magnet to be acceptable. The contract was then extended to 52 magnets and further production started. By the end of the year, ALSTOM was producing magnets at the planned rate of two per month.

TRIUMF is also designing and building 6 resonant charging power supplies (RCPS), 9 pulse forming networks (PFN), and 20 thyratron switch tanks for the LHC injection kickers. This work is being carried out at TRIUMF in a specially built clean room with overhead crane coverage. The RCPS were completed in 2000 and one of them was tested at 66 kV operation this year. The 9 pulse forming network tanks were assembled and tested satisfactorily at low voltage. There was excellent agreement between the pulse measurements and the PSpice predictions used for the design. Orders have now been placed for all of the components for the 20 switch tanks, with assembly scheduled for 2002.

The remaining technical work is an instrumentation task which involves the design and fabrication of electronics for the readout of the LHC beam position monitors (BPM). A prototype of this VME based data acquisition board (DAB) was successfully tested in the SPS beam during the summer of 2000. However, a decision at CERN to remove these electronics modules from the high radiation environment of the LHC tunnel required some redesign. Some additional features were also added. Laboratory tests were carried out at CERN in November on the revised design and satisfactory operation was demonstrated. Ten modules are now being produced for beam tests in 2002. TRIUMF has also arranged for the production of 2300 filter pairs for the analogue portion of the BPM readout.

The main beam dynamics involvement has been the design and optimization of the beam optics for the collimation insertions. The work this year was aimed at improving the robustness of the collimation system and making modifications to the design for cost savings. TRIUMF is also assisting with the study of beam-beam interactions at the LHC collision points using a simulation code developed at TRIUMF.

The LHC cost review carried out at CERN in the latter part of the year indicated that the cost-to-completion of the accelerator and experimental areas had increased by about 18% over the original estimate. The impact of this cost overrun on the completion schedule for the LHC is still not determined. In any case the components being provided by TRIUMF should be delivered as scheduled.

BEAM DYNAMICS

The simulation study of beam instability induced by interactions between the two beams at the LHC collision points has been extended to include the effect of "parasitic collisions" between bunches approaching and leaving the crossover; a promising start has also been made to include longitudinal motion within the bunches in the simulation. For the LHC collimation system, the priority was updating the cleaning insertion optics to take account of economy-driven changes in the magnet lattice. Studies of the robustness of the LHC collimation system against alignment and magnetic field errors were thereby delayed, but have now restarted with fresh impetus from the new Collimation Task Force at CERN. The study of resonance-free optics in the LHC was completed by investigations confirming its insensitivity to octupole and skew sextupole errors.

Coherent Beam-Beam Effects in the LHC

This year we continued to study coherent modes of beam-beam interactions using a simulation code based on a hybrid fast-multipole (HFM) field solver, originally developed at TRIUMF for space-charge calculations. Of particular concern are the so-called "parasitic collisions", where counter-rotating bunches of protons pass each other in close proximity as they approach the actual collision point. Although these long-range encounters involve weaker electric fields than the head-on collisions, there are many more of them and hence there is a greater potential to excite unstable modes.

We found that the HFM method, which easily accommodates varying distance scales, provides efficient and accurate field solutions for parasitic collisions, allowing a fully self-consistent multi-particle simulation. With traditional mesh-based field solvers, such simulations become prohibitively expensive due to the exponential scaling of computation time with the size of the solution region.

A number of different scenarios involving head-on collisions with different betatron tunes, beam intensities, and beam sizes, as well as early tests and results for long-range collisions, have now been studied [W. Herr *et al.*, Phys. Rev. ST Accel. Beams **4**, 054402 (2001)], with further long-range results to be reported in 2002. For both types of collision, the simulations revealed the expected coherent modes with frequencies in good agreement with analytical predictions.

For head-on collisions with equivalent beams, the potentially unstable π mode is isolated from the incoherent continuum of frequencies. On the other hand, sufficient differences of intensity, betatron tune, or beam size between the two beams will shift the π mode into the continuum, where it will be Landau-damped. Our simulation tool allows us to quantify these effects and hence predict what operational parameters are needed to avoid coherent beam-beam instabilities.

Later in the year, we began a new study of another issue relatively unexplored by simulation: the effect of longitudinal motion in coherent beam-beam interactions. Extending the model fully to three dimensions escalates the cpu requirements to the supercomputer realm. However, we have developed a longitudinal slicing algorithm that makes the problem tractable on a small computing cluster. The simulation code has been extended to support this model and has been tested on a single processor. In 2002 we plan to parallelize the code with MPI for use on a small Linux cluster being installed as a "seed" facility at TRIUMF.

LHC Collimation

Lattice work included rematching the beam optics for the collimation insertions in LHC Version 6.3. As a result of an engineering proposal for standardization of the connection cryostat (to save 0.5 MSF), the quadrupole Q7 (left and right, IR3 and IR7) had to be moved by 3 m. This was done without a serious loss of performance.

Improving the robustness of the collimation system was the main subject during the second half of 2001. This was done as part of the work of the CERN Collimation Task Force (see http://www.cern.ch/LHC-collimation), whose final statement is to be issued in November, 2002. Ongoing studies include: modification of the collimator set-up (probably longer collimators) to ensure protection against accidental impact on them by a large fraction of the LHC beam; modelling steady multi-turn losses with DIMAD; and a search for the most dangerous optical error that would affect momentum collimation.

Resonance-Free LHC Optics

This study was completed in 2001. Resonance-free LHC optics make it possible to cancel the effect of non-linear resonances. However, the resonance-free condition itself can be destroyed by large gradient errors. For nominal and resonance-free lattices we computed:

- $Q1''$ and $Q2''$, the second derivatives of tunes with respect to momentum, associated with the skew sextupole field error a_3;
- resonance driving terms and the reduction in long term dynamic aperture due to octupolar errors: b_4 and a_4.

It was demonstrated that resonance-free optics make it possible to tolerate the nominal a_3 error and 3–10 times the nominal b_4, a_4 errors, without taking advantage of their correction systems. Gradient errors three times larger than the nominal ones do not destroy these benefits (see Fig. 193).

CONTROLS AND INSTRUMENTATION

LHC Orbit System Components

The electronics intended to read out the LHC beam position monitors (BPM) comprise a calibrator, 70 MHz low-pass filter, wide-band time normalizer (WBTN), and 40 MHz digitization. As a result of radiation tests performed at CERN in 2000, it was decided to move much of the LHC BPM electronics out

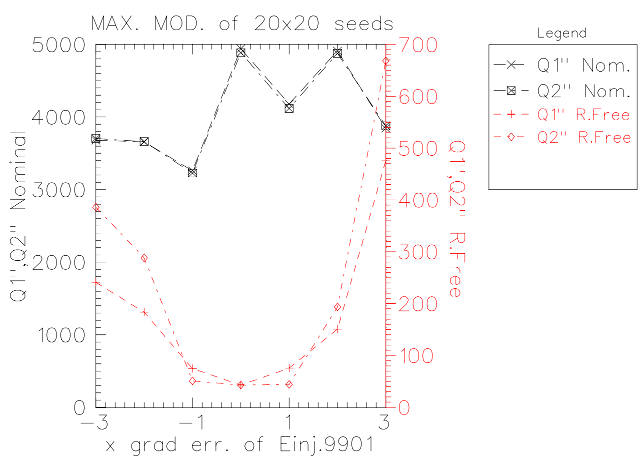

Fig. 193. Second order chromaticity (400 seeds) caused by skew-sextupole field error in main LHC bends. The resonance-free optics (right scale) have smaller parasitic chromaticity than the nominal, even for three times the nominal gradient errors.

of the radiation fields in the tunnel. This required redesign of the CERN normalizer and the TRIUMF digital acquisition board (DAB) which uses two complex programmable logic devices. The WBTN was repackaged as two modules: an analogue part remaining in the LHC tunnel, and a digital part moved to a mezzanine card on the DAB module. The WBTN analogue signal is transmitted through a 3 km fibre optic cable to the DAB II module which accepts two mezzanine cards, one for each plane of the BPM. After review of these changes, the specification document was revised in May and the following operation modes were defined:

- Orbit: continuous, real time closed orbit measurement.
- Capture: turn-by-turn measurement for selected/all bunches/batches and data averaging.
- Histogramming: record the distribution of data with one global orbit acquisition, and histogram for data validation.
- Post-Mortem: provide a history of the beam orbit and turn-by-turn position in order to diagnose and understand beam loss or sudden beam dumps.
- Calibration: asynchronous acquisition (not reliant on the 40 MHz bunch clock and the 11 kHz revolution frequency).

All three acquisition modes (orbit, capture and histogramming) can proceed in parallel. The post-mortem and histogramming additions resulted in considerable increase in design complexity, as did the decision to acquire horizontal and vertical signals without the beam synchronous timing. Unlike the first DAB prototype, the DAB II is not responsible for providing timing and control for WBTN calibration. Instead, so as not to rely on beam synchronous timing, calibration is done in the LHC tunnel using an oscillator on the WBTN front-end.

Three DAB II cards were assembled, including a "dummy" WBTN mezzanine card to simulate BPM data. After successful local tests of the redesigned hardware and application software, the cards were delivered in November to CERN where laboratory tests on the DAB/WBTN combination demonstrated their correct functioning. During this time the prototype LHC BPM system became operational in the SPS, and the bunch-by-bunch measurement capability was used extensively to understand the electron cloud instability which may limit LHC-beam intensity. Figure 194 shows the horizontal oscillation amplitude of each bunch in the LHC batch for 1000 turns. Marginal stability could be reasserted by changing the machine chromaticity.

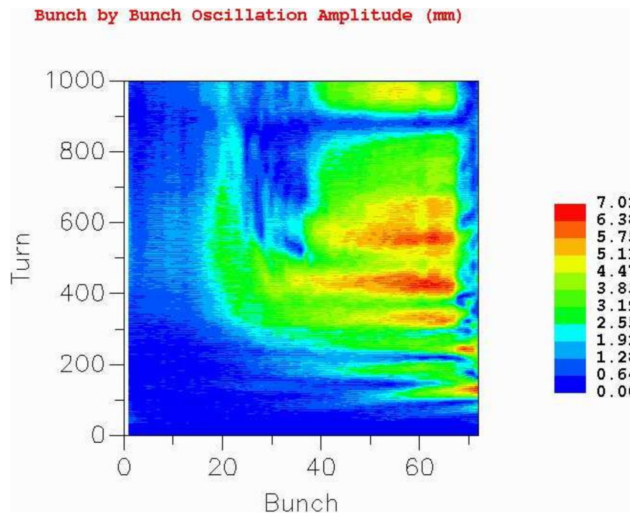

Fig. 194. Bunch-by-bunch oscillation amplitude (mm).

Although further hardware modifications will be required to correct minor problems with VME interrupt handling, and possibly to add further functionality, it is anticipated that ten DAB II modules will be delivered to CERN in June, 2002 for beam tests in the SPS and, depending on the outcome, 60 pre-production modules might be ordered in 2003.

Filter pairs

The matching criterion for the filter pairs now calls for the 3 dB corner frequencies to be within 1 MHz. The filter manufacturer, Lorch Microwave, promised that the time responses will match within 100 ps. The pre-production run of 150 pairs of 70 MHz low pass filters was received from Lorch in April. Ten pairs were retained at TRIUMF and 140 pairs were sent to CERN where testing of 26 pairs confirmed electrical measurements made by Lorch during the manufacture.

Testing of the radiation hardness of the filters was begun concurrently at CERN and TRIUMF in August. Three filters tested at TRIUMF, using a beam of 67.3 MeV protons with a dose rate of 7.3 Gy/min, were exposed to 200 Gy, which is the anticipated lifetime exposure at the LHC. Sensitive tests with a network analyzer found no change in electrical properties, and no corrosion was found when the irradiated filters were opened for inspection. The lengthy test at CERN, with an estimated dose rate of 20 Gy/week, accumulated an exposure of 900 Gy including the possibly more damaging effects of neutrons. CERN measurements confirmed no changes in the electrical properties and no corrosion. A mis-steered proton beam in the LHC could cause up to 2 W dissipation in the 50 Ω resistor inside a filter. At TRIUMF, a filter heated by 2 W rose 47°C in temperature and the time delay through it increased by 15 ps, which is considered acceptable. The other characteristics remained constant.

The production run of 2150 pairs arrived at TRIUMF in October, much ahead of the original delivery schedule. Lorch Microwave measured 13 electrical parameters of each filter and made this database available as an Excel spreadsheet. A LabVIEW program, interfaced to a network analyzer, will be used to test a 5% sample of the filter pairs, and shipment to CERN is anticipated in February, 2002.

MAGNET DEVELOPMENT

TRIUMF has agreed to provide CERN with fifty-two twin aperture resistive quadrupole magnets for the LHC cleaning insertions. In 1999, TRIUMF awarded ALSTOM Canada Inc. (Tracy, Quebec), a contract to manufacture the first 17 quadrupoles. During 2000, ALSTOM prepared tooling and started working on the first production magnet. Some technical difficulties in welding the stacks of laminations to the required straightness tolerance, and a period of labour problems, delayed completion of this first magnet. Mechanical measurements of the assembly accuracy are carried out with a special pole distance measurement device (PDMD) at the factory. This device measures the distance between flat-parts of the poles at four gaps for each aperture. The acceptance criterion requires a tolerance of $\pm 100\ \mu$m for 90% of the length of the magnet. Figure 195 shows the results for one of the apertures of the first magnet.

The first magnet satisfied these requirements and was air-freighted to France, arriving at CERN on March 5. CERN made preliminary mechanical and magnetic field measurements of the magnet, and on April 3, accepted the magnet. Measurements on the magnet were reported in a paper presented at MT17 [Clark, Proc. 17$^{\text{th}}$ Int. Conf. on Magnet Technology (MT17), Geneva, September 24–28, 2001 (IEEE Trans. Appl. Superconductivity, in press)].

After the first magnet was delivered, ALSTOM and TRIUMF negotiated the extension of the contract from

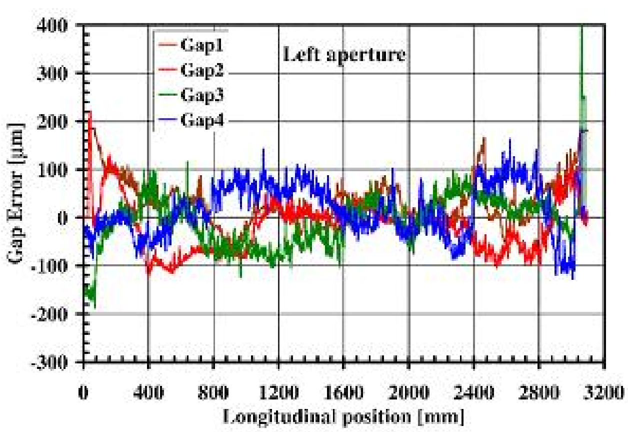

Fig. 195. Measured pole distance errors on MQW001 as a function of the longitudinal position in one of the apertures.

Fig. 196. Layout of the so-called TRIUMF shop at ALSTOM.

17 to 52 magnets. ALSTOM reorganized the project, bringing in a full-time project manager/engineer. The production shop was also reorganized and a second coil mold and stacking table fabricated to enable the magnets to be produced at a rate of two per month. DELSTAR Inc. (Montreal, Quebec), replaced SIGMA as the coil winder, with the coil insulation and impregnation continuing to be carried out at ALSTOM. Figure 196 shows the layout of the so-called TRIUMF shop at ALSTOM.

The year-end saw 3 production magnets at CERN and 3 magnets in transit to CERN. The production rate peaked at 3 magnets per month just before Christmas. ALSTOM expects to deliver at least 24 magnets in 2002.

The method of reviewing the quality of the two types of laminations punched for these magnets was also presented at MT17 [Clark, *op. cit.*].

KICKER MAGNETS

In collaboration with CERN, TRIUMF has designed and is in the process of assembling and testing 4 CERN LHC injection kicker systems plus spares. Each LHC injection kicker system will consist of 1 resonant charging power supply (RCPS), two 5 Ω pulse forming networks (PFN), 4 thyratron switch tanks, and 2 kicker magnets. The LHC injection kicker magnet systems must produce a kick of 1.3 T m each with a flattop duration which is variable up to 7.86 μs, a rise time of 900 ns, and a fall time of less than 3 ms. The combination of ripple and stability in the field from all kicker system components must be less than $\pm 0.5\%$. A prototype kicker magnet has been assembled at CERN and is ready for testing. Six RCPS, including the prototype, have been assembled at TRIUMF. The prototype has been extensively tested at CERN and one production model has undergone preliminary testing at 66 kV

Fig. 197. Four completed RCPS and 8 PFN in storage on the proton hall roof, prior to tests.

operation. Fully documented RCPS tests will be performed early in 2002. Nine PFN have been designed and assembled at TRIUMF and tested at low voltage. Figure 197 shows the completed PFN and RCPS in storage on the proton hall roof beams. Testing of prototype thyratron switch tanks has been completed at CERN, and design of the production models has been completed at TRIUMF. Orders have been placed for all of the components for 20 switch tanks that will operate at 66 kV.

RCPS

An RCPS has two parallel outputs, to charge two 5 Ω PFN to 66 kV. The RCPS has a 2.6 mF storage capacitor bank charged to 3 kV. A thyristor is used to switch the energy on the capacitor bank onto the primary of a 1:23 step-up transformer of low leakage inductance. The output of the secondary is transferred to two 5 Ω PFN through two coaxial cables, two diode stacks and two 70 Ω resistors. The RCPS is designed so that the PFN can be charged up to 66 kV in less than 1 ms at a repetition rate of 0.2 Hz.

The TRIUMF Kicker group has completed the series production of 5 RCPS, which incorporate several improvements over the prototype RCPS. The two dummy loads that were used for prototype PFN testing at CERN were returned to TRIUMF. New 1.1 μF dummy load capacitors rated at 66 kV, which were received from ZEZ Silko (Czech Republic), have been installed and tested. Each 1.1 μF dummy load represents a 28 cell PFN. A standard test procedure has been developed for RCPS to be tested at TRIUMF. The tests will proceed early in 2002.

PFN

Each 5 Ω PFN is composed of two parallel 10 Ω lumped element delay lines (Fig. 198) consisting of 4.3 m long precision wound coils, high voltage and high current capacitors, and damping resistors. There is a thyratron switch tank at each end of the 5 Ω PFN.

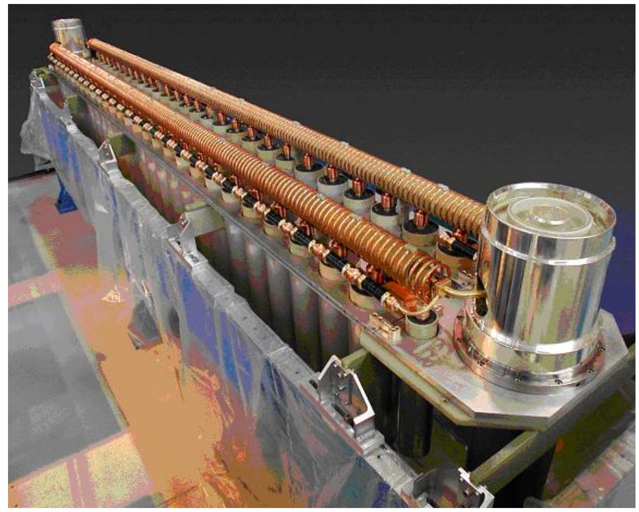

Fig. 198. One of 9 PFN under construction at TRIUMF.

Nine PFN have been built and tested at low voltage at TRIUMF to ensure that performance is within specifications. High voltage tests will be carried out following the manufacture of high voltage switch tanks at TRIUMF. The PFN were charged to 10.0 V and discharged into a precision 5 Ω load using a fast switching MOSFET with very low (11 mΩ) on-state resistance. The low voltage charging and switch circuits were modelled with PSpice in order to understand and therefore compensate for the measurement system calibration errors. Measurements in which the PFN was replaced with a 5 mF capacitor bank with a low parasitic inductance and series resistance established the calibration. All of the PFN, with numbering from 2 through 10, were measured without damping resistors installed; PFN #2 was measured with and without damping resistors. The ripple without damping resistors was less than ±0.5% on 8 of the 9 PFN, and ±1% on PFN #4. Voltage ripple for PFN #2, with damping resistors, was better than ±0.3%. The predicted kick rise time for PFN #2, from 0.2–99.8%, was 900 ns for a pulse with a flat-top of 8.54 μs duration and a ripple of less than ±0.2%, which meets the required specifications. There was no attempt to set up a low voltage dump switch to measure the fall time at low voltage. The absolute average measured flat-tops (Fig. 199) of the 9 PFN were within ±0.1% of each other, indicative of quality control during manufacture of the PFN. A procedure was developed for accurately measuring pulse performance of the PFN. The results of pulse measurements are compared with PSpice predictions in Fig. 200. There is a 0.25% discrepancy between the absolute value of the flat-top as measured and calculated by PSpice. However, the detailed shapes of the

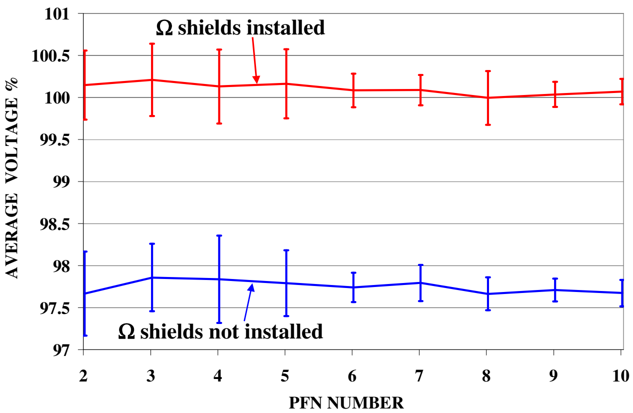

Fig. 199. Measured average flat-top voltage normalized to 200 V charging voltage (from 2 μs to 9 μs) with no damping resistors installed (error bars represent the maximum peak to peak ripple).

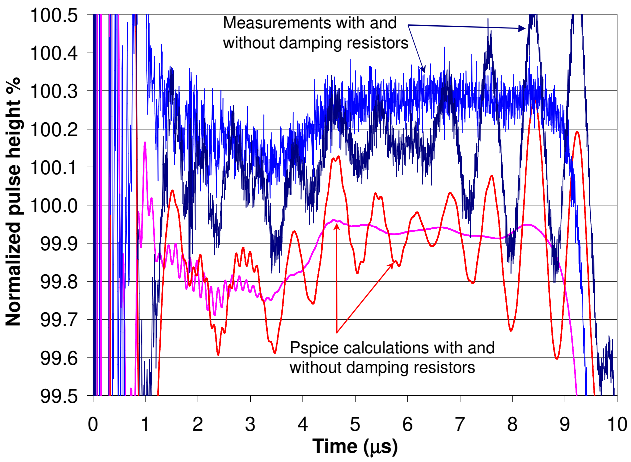

Fig. 200. PFN #2 measured and calculated pulse waveforms with and without damping resistors installed.

measured and calculated pulses are in excellent agreement.

Thyratron Switch Tanks

The thyratron switch tanks will mount on the ends of the PFN tanks. The main switch (MS) thyratron will be connected to a 5 Ω transmission line kicker magnet via 10 parallel 50 Ω coaxial cables, and the kicker magnet output is connected to a 5 Ω resistive terminator. The dump switch (DS) thyratron will also be connected to a 5 Ω resistive terminator.

The TRIUMF Kicker group, in collaboration with CERN, has designed a prototype HV grid/heater/reservoir bias circuit for the thyratrons. Two prototype bias circuits were built and bench tested at TRIUMF, and sent to CERN in September, 2000. CERN installed a prototype bias circuit in a prototype thyratron switch tank and completed power tests. CERN requested several modifications and a new feature. Two new bias boxes were built and bench tested at TRIUMF, and shipped to CERN in November. However, CERN has requested, following successful completion of power tests early in 2002, that TRIUMF supply 34 bias boxes; 20 of these will be used in the LHC injection kickers and 14 are to be used in the MKE (SPS extraction) CERN kicker system.

Redesign of all 20 thyratron switch tanks was completed. 184 drawings have been reviewed, all components have been ordered, and contracts awarded to the following machine shops: Sicom Industries (BC), Talvan (BC), Sunrise Engineering (BC), PDE, Acrodyne and Carleton University. Components started to arrive at the end of 2001, and most should be received in January/February, 2002. We expect to complete the design and place orders for the dump switch terminating resistor assemblies, thyratron transport jigs and lifting frames for the switch tanks early in 2002.

Specifications

Two specifications were issued.