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UNDER A CONTRIBUTION FROM THE
NATIONAL RESEARCH COUNCIL OF CANADA

DECEMBER 2003

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

TRIUMF's collaboration with CERN on producing accelerator components for the Large Hadron Collider (LHC) is nearing completion. As noted in last year's report three technical projects and two beam dynamics studies are presently being carried out. In October, the directors of TRIUMF and CERN signed an extension to Canada's agreement to contribute to the LHC project, adding a second contribution of \$11.5 million to the existing \$30 million. Most of these funds are being used to pay for the completion of the contract with ALSTOM.

The series production of the 52 twin-aperture quadrupoles for the beam cleaning insertions in the LHC is going very well at ALSTOM. By the end of 2002, 32 magnets had been produced and the production rate had increased to almost three per month. The magnets are now of high quality and the magnetic field measurements at CERN indicate that the harmonic content is acceptable. The speedy production rate together with a cost increase in the magnet contract meant that there is a cash flow problem this financial year and the next one. This was solved with a repayable loan of \$1.5 million from the National Research Council. ALSTOM now expects to complete the contract for the 52 magnets by August, 2003.

The other large contribution consists of components for the LHC injection kicker systems. The five resonant charging power supplies have been tested at high voltage into a dummy load. The nine pulse forming networks are completely assembled and tested at low voltage. The twenty switch tanks are nearing completion. High voltage testing will begin early in 2003 with the first major shipment to CERN about mid year. The shipping container used for the ATLAS calorimeter modules is being modified for shipping the kicker hardware.

A third version of the data acquisition board for the LHC beam pick-up monitors was delivered to CERN in July for testing. A fourth and hopefully final version is now being designed by TRIUMF. This version will be compatible with the newly adopted CERN VME64 standard and uses a new FPGA with more memory and therefore more capability is being requested by CERN.

Two beam dynamics efforts continue to be supported. The study of beam-beam interactions between the LHC beams at the collision points uses a simulation code developed at TRIUMF. This code is being extended to include the longitudinal motion and makes use of parallel computing to obtain acceptable computing time. The beam optics and collimation work is essentially a full time effort for a TRIUMF beam physicist. The collimation system protects the vacuum chamber in the region of the LHC superconducting magnets against beam losses. This year the Dimad technique developed at TRIUMF was compared with a tracking code used at CERN. At CERN it was realized that accidental beam dump failures could cause overheating of the copper collimators if a significant fraction of the beam was dumped locally over a single turn. The solution is to use longer collimators made of lighter material and this requires some changes in the optics to accommodate the longer collimator systems.

BEAM DYNAMICS

Coherent Beam-Beam Effects in the LHC

Our study of beam-beam interactions in the LHC seeks to identify potentially unstable coherent modes excited by the electric forces between counter-rotating bunches of protons as the two beams meet and cross in the collision regions. A multi-particle simulation code, based on 2D models of head-on and long-range interactions, has been used extensively to study these modes under various LHC operational conditions and crossing schemes. This year we entered a new phase of development in which our simulation code, newly dubbed BeamX, is being extended to include the third dimension and also to run in parallel computing environments.

Given the relatively long (0.3 m) bunches in the LHC, we wished to account for effects such as longitudinal motion, crossing angle, and size and density variations in the two beams as they cross each other. Longitudinal motion was included in the macro-particle tracking using the conventional stepwise integration as in many other tracking codes. For beam-beam interactions, a longitudinal subdivision (bunch-slicing) scheme was developed in which the interaction is decomposed into a series of 2D slice-slice interactions. To obtain acceptable computation time, it was crucial here to exploit the obvious parallelism, where, at each stage of beam-beam overlap, each slice-pair interaction (including field solutions and particle transport) can be done on a different processor.

We were fortunate to have unimpeded access to a small "commodity" Linux cluster set up as a test-bed by the Computing Services group at TRIUMF. This allowed some research into various options for parallelizing the simulation code, and led to the development of a suitable parallel algorithm using the MPI toolkit and the LAM environment in a communication topology involving both master-slave and slave-slave messaging. A novel aspect of the method is that it does not use any loops, but rather relies on the flow of interprocessor messages to optimally conduct the pairwise interactions of bunch slices.

The new code was tested with various numbers of slices and exhibited the expected linear speed-up, allowing us to begin full production runs. However, for a typical run (e.g. 7 slices) the turn-around time is still greater than one day on 1–2 GHz processors, so in 2003 we will likely be seeking further economies, either by improving the communication scheme or by further parallelization, e.g. of the field solver. In addition to ongoing support from TRIUMF resources, this project has been granted access to the University of Alberta THOR cluster, which offers more advanced communication hardware and larger numbers of processors.

Beam Optics and Collimation

Studies performed this year had the goal of verifying that the collimation system protects the vacuum chamber in the arcs against secondary halo protons in conditions close to operational, i.e. for particle beam, optics, and collimator alignment, all with imperfections. The need to treat correctly the off momentum halo implies that arc sextupoles must be included and a fully chromatic model of the ring has been adopted for multi-turn particle tracking by the program Dimad, which now includes the Monte Carlo module from the program Struct which simulates particle-in-media propagation.

As a benchmark, the inefficiency of the ideal system has been computed with Dimad and the results compared with those from a tracking program developed at CERN by Assmann, and the deviation between them attributed to different Monte Carlo models of the scattering; Dimad reports a factor 2.5 larger inefficiency.

By approximating the vacuum chamber around the ring by a pipe of 2 cm radius, and assuming the use of 50 cm long copper secondary collimators, the losses corresponding to steady operation have been evaluated both at injection and collision. For injection energy only, orbit error and collimator misalignment were included and tolerances were set. An important result is that the chamber wall losses are caused mainly by a highly off-momentum halo generated by energy losses as particles traverse the collimators.

The schematic shows a sample error orbit at injection (Fig. 244). The orbit is corrected with four kicks placed at the entrance and exit of each IR3 and IR7. The errors are closed orbit 4 mm peak-to-peak in the arc, and random transverse jaw misalignment with amplitude 0.5 mm. The fractions of halo lost in different vacuum chamber sections are given in Table XLVI.

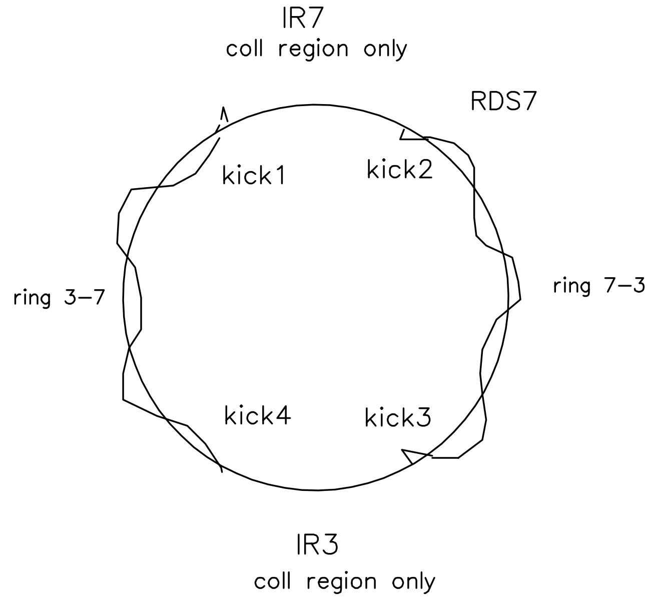

Fig. 244. Dimad model of the LHC ring with a sample error orbit.

Table XLVI. Simulated loss rates on the vacuum chamber wall within the right dispersion suppressor of IR7 (RDS7) and total in all arcs (ring 7-3 plus 3-7, see Fig. 244).

	No errors	With errors
RDS7	1.35×10^{-3}	2×10^{-3}
Arcs	1.6×10^{-4}	7.6×10^{-4}

It was concluded, based on the halo consideration, that the nominal system satisfies the design criteria, and this opinion is held by the CERN team also. However, it was realised recently that accidental dump failures (expected to happen at least once per year) may cause a large fraction of the LHC beam to impact one or several collimators in a single turn. The presently foreseen copper jaws can withstand only 2×10^{-5} of the total beam intensity, which is about 400 times less than the accidental loss. To rectify this, CERN has adopted longer secondary collimators made of lighter material. The next task is to provide around 3 m space for each collimator tank, by changing both optics and collimator locations, and to minimize any loss of performance.

CONTROLS AND INSTRUMENTATION

LHC Orbit System Components

The data acquisition board (DAB) is intended to process signals from the wide-band time normalizer units (WBTN) of the LHC beam pick-up monitors (BPM). The DABII revision, delivered in 2001, differed from DABI by the addition of histogram and post-mortem functions. The DABIII version designed and assembled this year adds a further capability: to replace, optionally, the position card with a fast integrator card to support a beam current transformer (BCT) application. In addition to some hardware fixes, the DABIII includes the following hardware modifications:

- Monitoring for all WBTN power supplies.
- Extra control pins to WBTN interface to support the BCT integrator mezzanine.
- Extra pins on VME interface for ±15 V to BCT integrator module.
- Improved functionality for selecting test signals for front panel monitoring.
- LVDS buffering for the turn clock and 40 MHz bunch clock signals.

After successful local tests of the design and its application software, nine DABIII cards were delivered to CERN in July: six for the SPS position measurement, one card for the BCT, and two for laboratory tests with a revised WBTN mezzanine module. Trajectory and orbit acquisition modes were fully tested including batch and bunch sum modes. In the last machine development period of the year the transverse positions of 4 batches of bunches were individually monitored at each of 4 BPM locations during the injection and acceleration process in the SPS (which is a test bed for LHC). Figure 245, which confirms a 50 μm resolution, shows example signals from individual batches at a single BPM. In another test, the WBTN was replaced with the BCT mezzanine and the DABIII was successfully used for bunch by bunch intensity measurements, as shown in Fig. 246.

Following the lead of the LHC experiments, the CERN controls group has adopted the VME64x chassis; a new DABIV compliant with this standard will be developed during 2003. In addition to new 12-bit look-up tables for horizontal and vertical trajectory data normalization, the final prototype card will incorporate a VME64x front panel, plug-and-play compatibility and other features including:

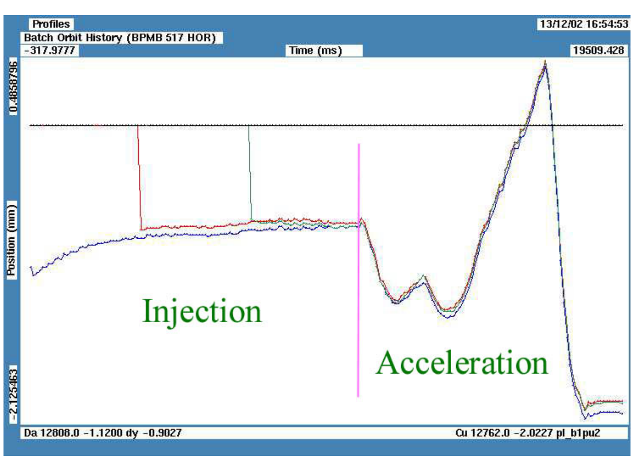

Fig. 245. Signals of three batches (red, green, blue) at a beam position monitor in the SPS.

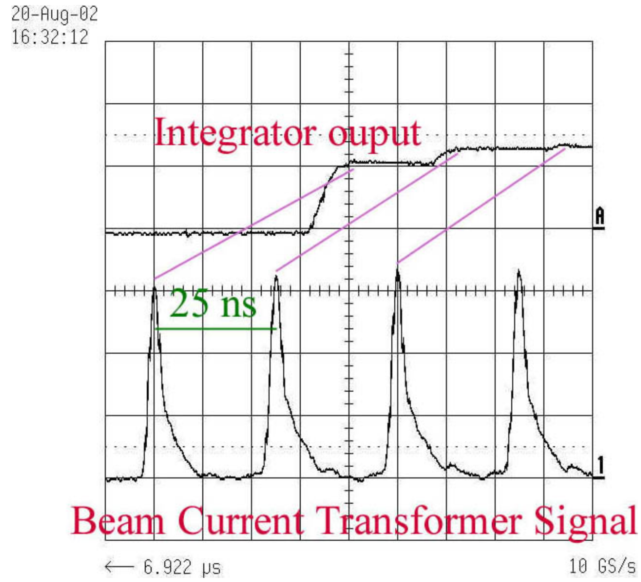

Fig. 246. Time domain signal, and its integral, from 40 MHz bandwidth current monitor in the SPS.

- Two post mortem memories.
- On-line offset subtraction for BCT integrator.
- VME64x configuration/status registers for system auto configure.
- Solder-side covers for hot swap.
- Electrostatic discharge protection.
- Maintenance bus for JTAG board diagnosis.

Filter pairs

2150 pairs of matched filters were purchased from Lorch Microwave for use in the LHC beam position monitor circuits. A network analyzer, driven by a custom-written LabVIEW program, was used to test a sample of 85 of the filter pairs. Early in March, the filters, along with the TRIUMF measurements and the manufacturer's production data, were delivered to CERN.

MAGNET DEVELOPMENT

Series production of the twin-aperture resistive quadrupole magnets for the LHC cleaning insertion began at ALSTOM Canada Inc. (Tracy, Quebec) with an order placed for the first 17 magnets in September 1999. In 2001, the contract was extended from 17 to 52 magnets after the funding was assured from the new five-year plan, and ALSTOM delivered 3 production magnets. In 2002, ALSTOM delivered 29 more magnets bringing the total to 32. Figure 247 shows the production schedule that has been achieved to date. The original estimate called for magnets to be produced at a rate of two per month. Recently ALSTOM is producing a magnet every 10 to 12 days and now expects to finish the contract in August, 2003.

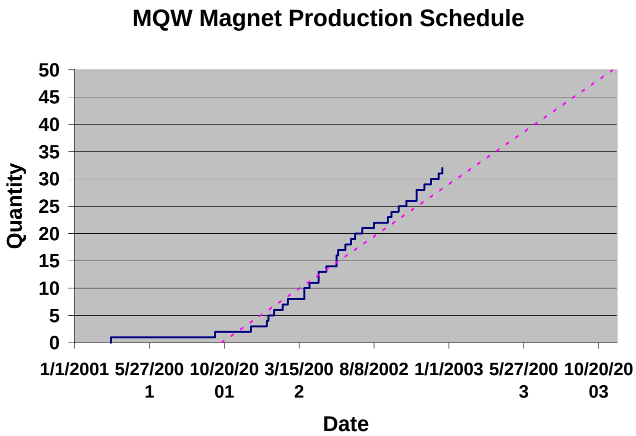

Fig. 247. Production schedule achieved to date.

Prior to shipping the magnets to CERN, a number of acceptance tests are carried out at the factory. These include the alignment measurement with the pole distance measurement device, electrical, water flow and temperature measurements and excitation of the magnet to the nominal peak current of 710 A. The magnetic field is measured using a hall plate mounted on a special holder for reproducible location in the quadrupole field. The acceptance tests are witnessed by an independent local firm LVM Fondatec Inc., with reports sent to TRIUMF to get shipping approval. TRIUMF and CERN engineers have visited the factory several times during the year for more detailed discussions on the progress of the contract.

Detailed magnetic field measurements are carried out at CERN using a rotating coil arrangement to determine the harmonic content of the magnetic field. Figure 248 shows several of the quadrupole magnets and the CERN team collaborating on this project. Table XLVII lists some of the relevant parameters measured during the accurate field mapping of the first few magnets. By the end of 2002, 9 magnets had been measured at CERN.

Fig. 248. Several quadrupole magnets and the CERN team collaborating on this project.

Table XLVII. Relevant parameters measured during accurate field mapping of the first few magnets.

	Current A	Left Aper n=2 Integ.	Right Aper n=2 Integ.	Left Aper n=3*	Right Aper n=3*
MQW001	710	0.4385	0.4377	–39.7	45.7
MQW008	710	0.4368	0.4367	–43.6	47.1
MQW010	710	0.4390	0.4395	–43.4	44.4

KICKER MAGNETS

In collaboration with CERN, TRIUMF has designed and built 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 (PFNs), 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 flat-top duration variable up to 7.86 μs, a rise time of 900 ns, and a fall time of less than 3 μs. The combination of ripple and stability in the field from all kicker system components must be less than $\pm 0.5\%$. A full size prototype kicker magnet has been built and tested at CERN up to 60 kV with the magnet under ultra high vacuum. Nine PFNs have been designed and completely assembled at TRIUMF, with all damping resistors installed and tested at low voltage. The design of the thyratron switch tank and the terminating resistors was completed. Twenty switch tanks are close to completion and the components for 10 terminating resistors have all been received. High voltage testing will commence early in 2003 with the first major shipment to CERN in mid 2003.

RCPS, PFN and Thyratron Switch Test Area

The kicker lab has been reconfigured to accommodate 4 racks of CERN controls which have been interfaced to a RCPS (Fig. 249) which is set up to pulse either 2 off of 66 kV dummy loads or one dummy load and one PFN. The control system computers are connected to CERN via the internet to allow CERN to update control software. The control system commissioning has been completed.

Cable trays have been installed, as well as a copper ground plane under the RCPS racks, the CERN control racks, the PFN test area, and the dummy loads. The front of the cabinets shown in Fig. 249 are in the low voltage area. The high voltage area is fenced off behind and beside the cabinets and contains the PFN, switch tanks under test, and the dummy loads. The gates to the HV area are interlocked. High voltage testing is anticipated to begin in the spring of 2003.

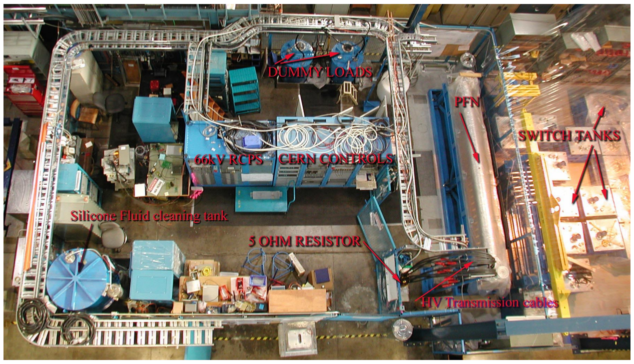

Fig. 249. CERN control system interfaced to PFN, dummy loads, and RCPS, ready for HV tests at TRIUMF.

RCPS

An RCPS has two parallel outputs to charge two 5 Ω PFNs to up to 66 kV. The RCPS has a 2.6 mF storage capacitor bank charged to up 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 (PFNs) through two coaxial cables, two diode stacks and two 70 Ω resistors. The RCPS is designed so that the PFNs can be charged up to 66 kV in less than 1 ms at a repetition rate of 0.2 Hz.

Six RCPS, including the prototype, have been assembled at TRIUMF. The prototype RCPS has been extensively tested at CERN. All of the 5 production models have been successfully tested at TRIUMF at 66 kV operation into two dummy loads. An extensive maintenance manual is almost completed and will be stored on CDs.

PFN

Each 5 Ω PFN is composed of two parallel 10 Ω lumped element delay lines 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. Nine PFNs were built in 2001 without damping resistors installed and tested at low voltage at TRIUMF. The damping resistors were installed in 2002 and the tanks then filled with silicone fluid to cover the resistors. Seven hundred litres of silicone fluid are required to cover the resistors, and an additional 325 l for high voltage operation. It is necessary to store the resistors in silicone fluid; otherwise the resistance values can change considerably. All of the PFNs, with numbering from 2 through 10, were measured with damping resistors installed: the ripple with damping resistors is less than ±0.2% on all 9 PFNs and the spread in the average magnitude is ±0.3% (Fig. 250). The pulse duration of all PFNs, from 50% of the rise time to 50% of the fall time, is 10.82 μs ±15 ns. The results of low voltage measurements are in excellent agreement with PSpice predictions.

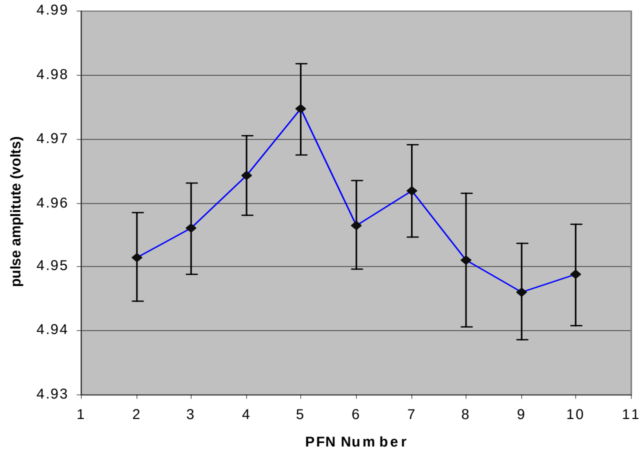

Fig. 250. Average PFN pulse amplitude (2 μs to 9 μs) for 10 V PFN charge error bars show peak ripple. All PFNs complete with damping resistors and filled with silicone fluid.

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. The dump switch (DS) thyratron will also be connected to a 5 Ω resistive terminator mounted on top of its switch tank (Fig. 251).

The TRIUMF Kicker group in collaboration with CERN has designed a HV grid bias circuit for the thyratrons. TRIUMF has built and tested 37 bias boards; 20 of these will be used in the LHC injection kickers, 14 have been sent to CERN for use in the MKE (SPS extraction) CERN kicker system, and there are 3 spares. The bias circuits will be installed in the thyratron switch tanks in early 2003 (Fig. 252).

We have received 3 thyratrons from CERN that need to be assembled into switch tanks for HV tests.

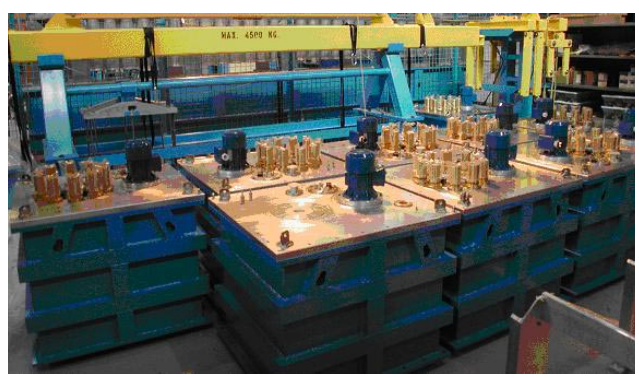

Fig. 251. View of some of the 20 assembled thyratron switch tanks at TRIUMF.

Fig. 252. One of the bias boards, without Faraday cage, cover mounted in a dump switch tank.

Terminating resistors

We completed the design for the dump switch terminating resistor assemblies, placed orders for their fabrication, and received all components by the end of 2002. We plan to start assembly of these high power terminating resistors in February, 2003.

Shipping container

We obtained a 20 ft shipping container that was used to ship components of the ATLAS detector from TRIUMF to CERN. We have made preliminary designs to permit RCPSs and PFNs to be mounted in the container for shipping; shock absorbers are built into the shipping container. The roof and back of the container must be modified for the CERN RCPSs and PFNs. Over the next two years the container will make 6 round trips to CERN for shipment of the LHC kicker system components.