TRIUMF

ANNUAL REPORT
SCIENTIFIC ACTIVITIES
2003

ISSN 1492-417X

**CANADA'S NATIONAL LABORATORY
FOR PARTICLE AND NUCLEAR PHYSICS**

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UNDER A CONTRIBUTION FROM THE
NATIONAL RESEARCH COUNCIL OF CANADA

DECEMBER 2004

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 another year closer to completion. For the period 1995–2005 the contribution that TRIUMF is coordinating on behalf of Canada is worth $41.5 million. The highlight of the year was the completion of the largest part of this contribution, the contract with ALSTOM Canada Inc. for the fabrication of 52 twin-aperture quadrupole magnets. The first prototype magnet was delivered to CERN in May, 1998, and the 52nd series magnet was delivered in August, 2003.

The other large contribution consists of components for the LHC injection kicker systems. The five resonant charging power supplies are complete and were acceptance tested this year. Four of the supplies were shipped to CERN in the container that was previously used for shipping the ATLAS calorimeter modules. The fifth supply will remain at TRIUMF for final testing of the pulse forming networks (PFNs).

High voltage testing of the 9 PFNs and the 20 switch tanks was started in 2003, and 5 of the PFNs and 10 of the switch tanks were successfully tested by the year-end. Shipment of the PFNs to CERN will start in March, 2004 and take about a year to complete with the turn-around time of the container.

The other hardware project is the design of the data acquisition boards for the LHC beam pick-up monitors. The third prototype version, DABIII, was delivered to CERN in 2002 for testing. The specification of the fourth and hopefully final version, DABIV, was completed during 2003. This version will be compatible with the newly adopted CERN VME64x standard and requires a new FPGA chip with more memory and increased processing power. At year-end it was in the final stages of design, with 5 prototype modules to be delivered to CERN by May, 2004. Eventually about 1200 of these modules are required and there are still discussions with CERN on how this can best be achieved.

Two beam dynamics efforts continue to be supported. The beam optics and collimation work became a high priority for CERN this year and much effort was made by the LHC collimation project team, including the TRIUMF beam physicist, to develop a final design. New criteria for the collimation scheme, increased space for longer collimators and decreasing the contribution by the collimators to the ring impedance, had to be incorporated into this design. Final designs of the betatron collimation section IR7 and the momentum collimation section IR3 were established by year-end.

The study of beam-beam interactions between the LHC beams at the collision points, which uses a simulation code developed at TRIUMF, is very computer intensive. This year, use of a small Linux cluster at TRIUMF and a larger system in Edmonton allowed further simulations to be carried out. The plan is to migrate this task to the WestGrid facility in 2004.

More details of the LHC work can be found in the following sections.

BEAM DYNAMICS

Beam Optics and Collimation

During the first half of 2003, exact agreement was demonstrated between the CERN tool for predicting collimation efficiency and the local code (DIMAD–STRUCT). The discrepancy reported in 2002 was attributed to the different treatment of off-momentum halo particles.

Subsequently, some important changes in optics and layout were made in the LHC *betatron* collimation insertion (IR7). In close collaboration with the LHC collimation project and optics team leaders, around 10 solutions for the IR7 were examined, both very old versions (dating back as far as 1998), and more recent lattices (late 2003). The main objectives were: 1) to generate additional space for longer collimators (4 m per secondary, instead of 0.7 m in the old design); and 2) to maximize the β-functions at the collimator jaws and thereby decrease the contribution of collimators to the ring impedance.

The low-impedance requirement represents a conflict with previous requests. A good cleaning efficiency and aperture had to be simultaneously maintained, which led to a severely constrained optimization problem. The code Distribution of Jaws (DJ) was modified so that, for a given optics and collimators, the impedance is computed and minimized along with the usual halo related quantities.

With collimators occupying as much as 40% of the total available space in IR7 (128 m of total 341 m), and in some cases being inserted between two warm quadrupole modules, each new collimator distribution also requires shifts of warm modules (up to 10 m). For each case, the optics rematching was done at TRIUMF, while the (tracking) efficiency was tested at CERN.

As a result, the initial design approach was confirmed. The final IR7 optics chosen (Fig. 302) is very close to the previous LHC version 6.4 and preserves the number of collimators and warm quadrupoles, and the maximum voltage of the power supplies. The new optics provides larger betatron phase advance across the insertion, and the wider domain of phases at intermediate locations makes possible the positioning of collimators at positions of higher $\beta_{x,y}$.

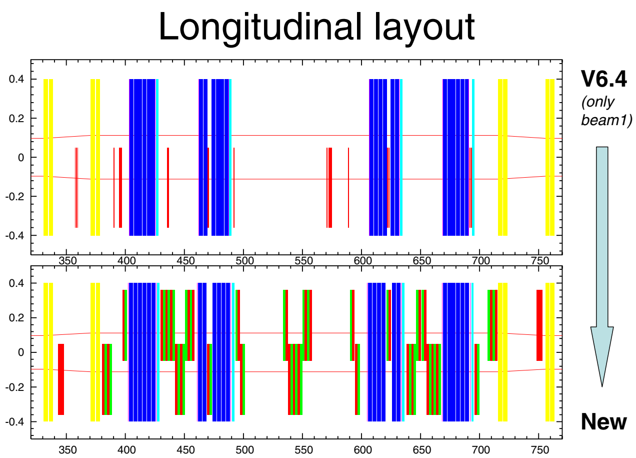

Fig. 302. Layout of the IR7 cleaning insertion. The MQW quadrupoles are shown in dark blue.

In addition, a single revision was made to the *momentum-collimation* insertion (IR3): two of the original six collimators were eliminated and the remaining four secondary collimators were set at new locations and rotation angles computed with DJ.

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. Large-scale multiparticle simulations are a principal tool in this type of investigation and in 2002 our beam-beam simulation code BeamX became one of the first to include a fully 3-dimensional model of the collision process. Of necessity this involved parallelizing the code and finding suitable parallel computing resources.

This year we made extensive use of a small Linux cluster at TRIUMF, and the University of Alberta Physics Department's THOR cluster which offered more advanced communication hardware, in order to debug, optimize, validate, and extend the BeamX code. With the basic longitudinal effects (phase oscillations, density variation, hourglass effect) already in place, we added the treatment of the beam-beam crossing angle, which affects the strength of the beam-beam force and introduces synchro-betatron coupling, resulting in sidebands in the coherent spectrum (Fig. 303).

Since BeamX has several output streams and can produce typically ∼50 Mbytes of data per run, the logistics of run management and documentation becomes an issue, especially when doing simultaneous runs in Vancouver and Edmonton, and analyzing the results at CERN. To ease this, a working protocol was developed which uses tools such as ssh, rsync, and Matlab, to configure and propagate the simulation runs, and to store, process, and replicate the data.

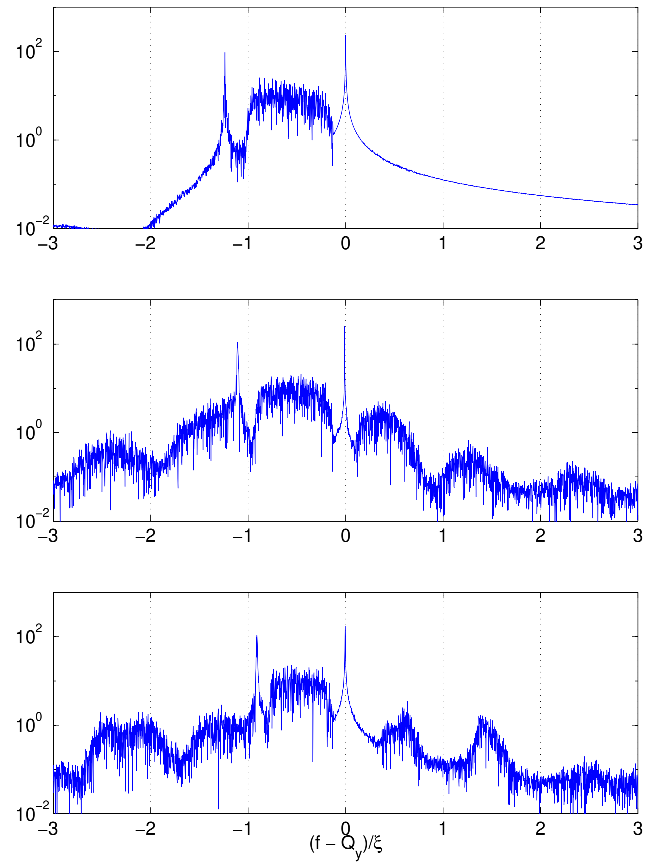

Fig. 303. BeamX: spectra (FFT of beam centroid) for 0, 100, and 300 μr beam-beam crossing angle.

For optimization, the main concern was to minimize interprocess communication bottlenecks and thereby improve the parallel efficiency. The arrangement of master-slave and slave-slave message passing (see Fig. 304) was further generalized to have the least possible dependency on message ordering. This yielded some improvement, but there is still some under-utilization

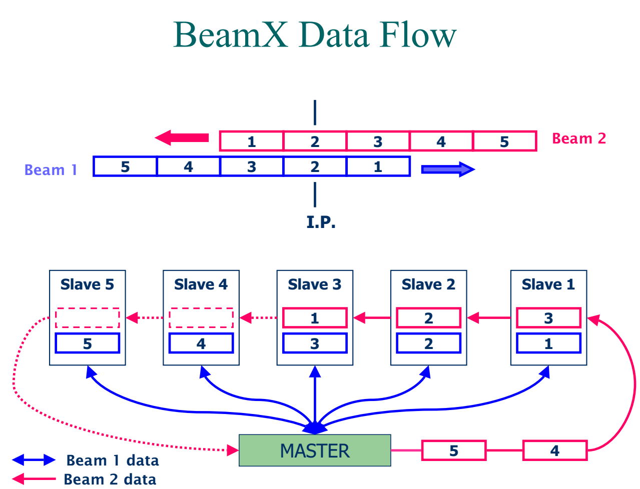

Fig. 304. BeamX: mapping of beam-beam interaction to parallel process and inter-process communication.

of processors due to the large volume of particle coordinate data being transmitted and to unequal load-balancing between processes.

In 2004 we expect to migrate the computing task to the new WestGrid facilities, which include a large multiprocessor shared-memory system that will be an alternative to the message passing approach, given the program's memory-intensive requirements. Evaluating this and other WestGrid platforms will entail further development, profiling and benchmarking exercises. This should yield better knowledge about the program behaviour and about which parallel architecture will best allow us to explore the parameter space of beam-beam collision scenarios contemplated for LHC operation.

CONTROLS AND INSTRUMENTATION

LHC Orbit System Components

The DABIII data acquisition boards delivered and tested at CERN in fall, 2002 were a consolidation of the DABII design with minor hardware modifications. The subsequent request for a VME64x compliant DABIV module with a substantial increase in processing power and memory requirements necessitated the adoption of a new higher density "Stratix" Altera chip set with 10 times the internal memory. Additional module requirements included: JTAG compliant multidrop "scan bridge" interface for module testing, 2×12-bit look-up tables for beam current transformer (BCT) integrator, and for trajectory data normalization, auxiliary post-mortem memories, VME64x compliant interface and 64-bit data transfers, extra registers for system auto configure, flash memory for power-up configuration, and a new EMC/ESD front panel. After a flurry of activity to define these requirements, work on this project stalled for most of the year due to manpower constraints. Minor progress was made on debugging existing code running in the DABIII and analyzing the VME64x specification to determine additional hardware requirements for the new DABIV module. It is anticipated in 2004 to procure new hardware, redraw module schematics, lay out the new PCB, rewrite embedded control firmware and fabricate 5 prototype modules for delivery to CERN in May. An additional 30 modules will be delivered for beam tests in September.

MAGNET DEVELOPMENT

The largest piece of TRIUMF's contribution to the LHC was completed in August, with delivery of the last of 52 twin-aperture quadrupole magnets to CERN. Seventeen magnets were delivered in 2003. These warm magnets (48 plus 4 spares) will be installed in the two beam cleaning insertions of the LHC, where heating by lost beam prohibits the use of superconducting coils. The so-called MQW magnets, based on a CERN design, were fabricated by ALSTOM Canada Inc. (Tracy, Quebec) with considerable input and design assistance from TRIUMF and CERN engineers. Their small apertures (46 mm) and high gradient (35 T m) meant that the 3.4 m long modules had to be assembled with unusually high tolerances to achieve the necessary field quality.

A prototype magnet was completed and shipped to CERN in May, 1998 for mechanical and magnetic field measurements. As these measurements showed that the desired field quality had not been achieved, improvements were made in the lamination design, in the punching precision, and in welding the stacks of laminations without distortion. Stronger stacking tables and a separate half-magnet assembly table were also constructed. These changes led to the first series magnet completed in March, 2001, fully meeting specifications. ALSTOM then proceeded to meet and eventually surpass their planned production rate of two magnets per month.

Figure 305 shows the delivery schedule for the 52 magnets relative to the estimated schedule of 2 magnets/month. Figure 306 shows the last delivered

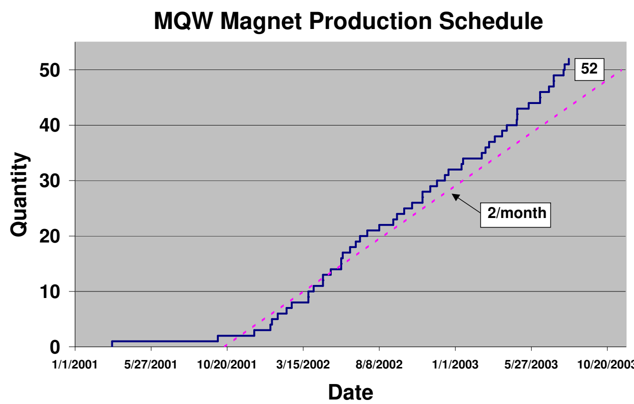

Fig. 305. Delivery schedule for 52 magnets.

Fig. 306. Last delivered magnet with ALSTOM team.

magnet together with the ALSTOM team that produced it. Mechanical measurements were carried out at the factory to qualify the magnets prior to shipping, with detailed magnetic field measurements being made at CERN.

KICKER MAGNETS

In collaboration with CERN, TRIUMF has designed and built all of the resonant charging power supplies (RCPSs), pulse forming networks (PFNs), thyratron switch tanks and dump switch (DS) termination resistors for the CERN LHC injection kicker systems. The kicker magnets and associated terminating resistors are being built at CERN. Each of the two LHC injection kicker magnet systems must produce a kick of 1.3 T m with a flat-top duration variable up to 7.86 μs, and rise and fall times of less than 900 ns and 3 μs, respectively. A kicker magnet system consists of four 5 Ω transmission line magnets with matching terminating resistors, four 5 Ω PFNs and two RCPSs. The combination of ripple and stability in the field from all kicker system components must be less than $\pm 0.5\%$.

RCPS

An RCPS has two parallel outputs to charge two 5 Ω PFNs up to 66 kV. 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 and tested at 66 kV on 2 dummy loads at TRIUMF. The prototype RCPS has been extensively tested at CERN. Representatives from CERN visited TRIUMF in May and carried out successful acceptance tests with 2 of the RCPSs and 2 PFNs. Four of the RCPSs were shipped to CERN and received on December 19. One RCPS remains at TRIUMF in the kicker HV test lab to be used for completion of the HV tests on the PFNs. Figure 307 shows 5 completed RCPSs ready to ship.

Fig. 307. Five RCPSs completed and ready for shipment.

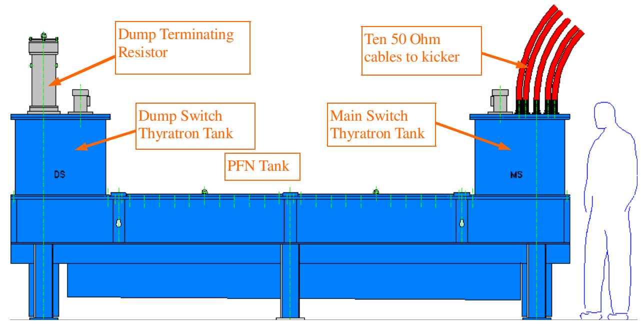

Fig. 308. PFN with thyratron switch tanks, dump switch terminating resistor, and HV cable.

PFN

Each 5 Ω PFN is composed of two parallel 10 Ω lumped element delay lines; each line consists of a 4.3 m long precision wound coil, with high voltage and high current capacitors and damping resistors in parallel with the coil. There is a thyratron switch tank at each end of the 5 Ω PFN (see Fig. 308).

Nine PFNs were built in 2001 and tested at low voltage in 2002. High voltage testing began in 2003. Five PFNs, 10 switch tanks and 5 terminating resistors have been completely HV tested. The high voltage tests on the remaining 4 PFNs will be completed by the end of February, 2004. Figure 309 shows

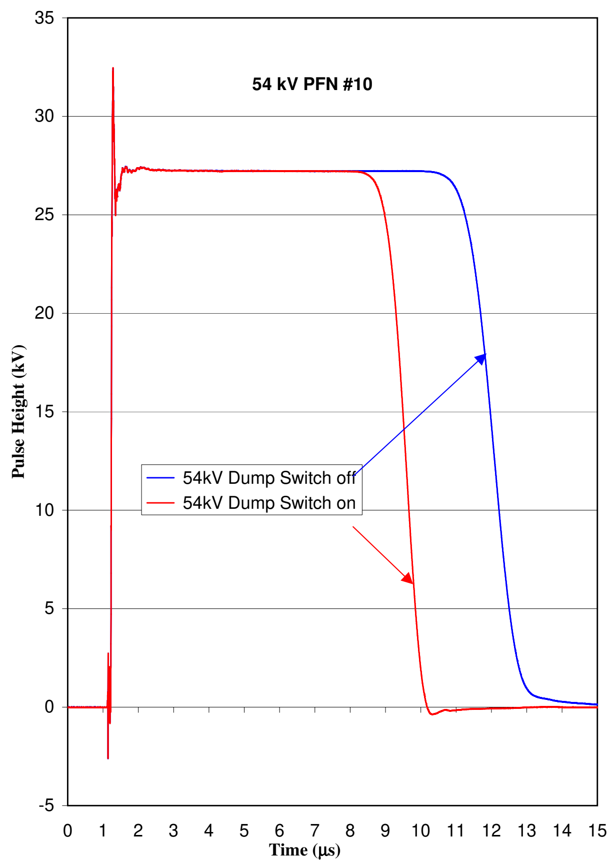

Fig. 309. 27 kV pulses from 54 kV PFN tests with and without triggering the dump switch thyratron.

Fig. 310. 5 PFNs have been tested at high voltage and are ready to ship to CERN.

27 kV pulses obtained from 54 kV PFN tests. The maximum variation in absolute pulse heights in the 5 PFNs tested so far is ±0.08%.

Two PFNs with their switch tanks mounted have been assembled with locking bars in place and foam padding installed above the Ω shields and are ready for shipping. Figure 310 shows a photo of the PFNs ready to ship.

Thyratron Switch Tanks

All 20 thyratron switch tanks, which mount on the ends of the PFN tanks, have been completed (Fig. 311). The main switch thyratron will connect 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. A 5 Ω resistive terminator is mounted on top of the DS tank (Fig. 312). Each switch tank contains a bias board that puts a dc bias on each of 2 thyratron grids. TRIUMF has designed, built and bench tested 37 bias boards; 20 of these have been installed in the thyratron switch tanks at TRIUMF, and 14 have been sent to CERN to be used in the MKE (SPS extraction) system. However, when high voltage tests were carried out at CERN and TRIUMF, there was a failure in the bias board at between 25 kV and 30 kV PFN voltage. The failure, which was a voltage to frequency converter integrated circuit, did not prevent operation, but did prevent the read-back of the grid #1 bias voltage via the voltage to frequency converter and a fibre optic link. The bias board "ground" has a 30 kV transient imposed on it with a 30 ns transient time. After many trials and re-arrangements of "ground" circuitry and added filtering, a final successful design was obtained at TRIUMF, such that there have been no further failures in the 10 switch tanks that have been tested at 60 kV.

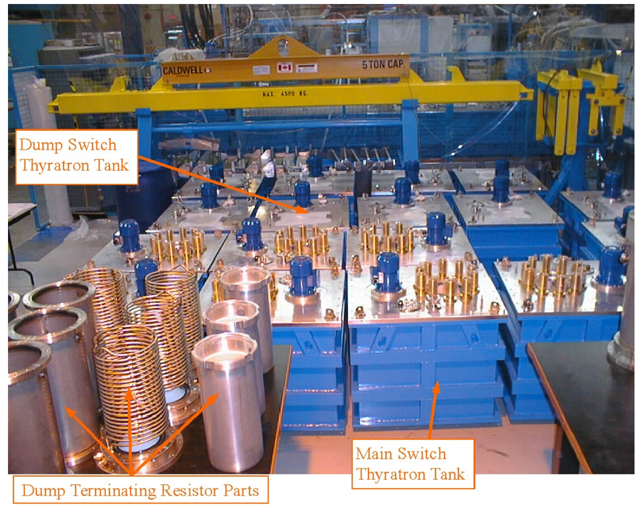

Fig. 311. Thyratron switch tanks assembled.

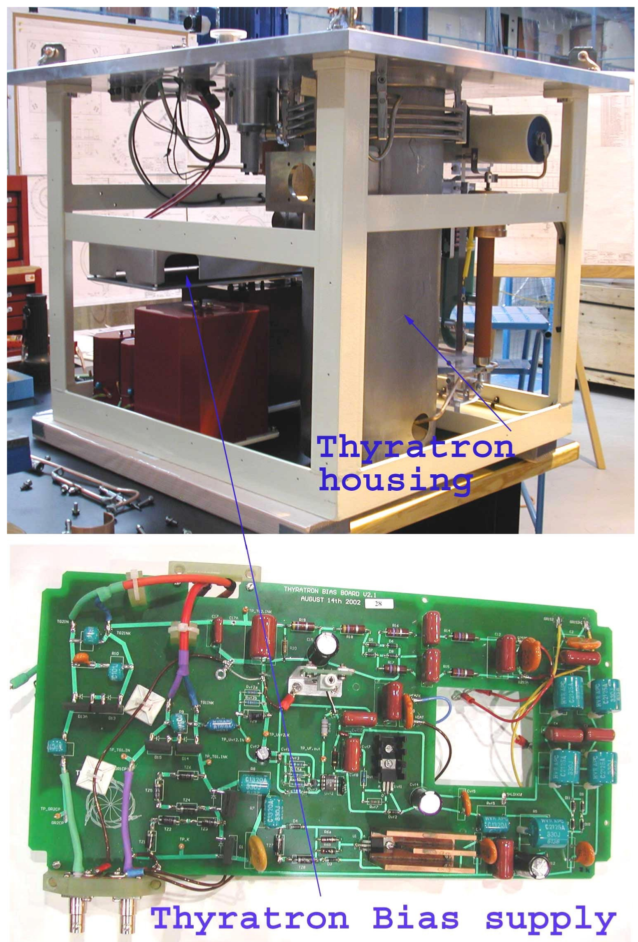

Fig. 312. Modified bias board and internal parts of thyratron switch tank.

Shipping Container

The TRIUMF ATLAS shipping container was generously donated to the Kicker group after the last shipment of the ATLAS detector components from TRIUMF to CERN in 2003. The roof and door of the container have been modified for shipping of kicker components. A new shock absorbing frame was designed and installed in the container. The shock absorbing frame was designed to allow for shipment of the 4 RCPSs in the first shipment, which left TRIUMF in October, and to allow for shipment of 2 PFNs at a time in subsequent shipments. The turn-around time for the container is approximately 3 months. PFN mounting clamps will be fabricated in early 2004 and the first shipment of 2 PFNs will occur in early March, 2004. The final shipment will be in early March, 2005.