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UNDER A CONTRIBUTION FROM THE
NATIONAL RESEARCH COUNCIL OF CANADA

DECEMBER 2006

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 now complete in terms of hardware deliverables. The last of 6 shipments of kicker components arrived at CERN in September. The installation of the kicker PFNs has started in the LHC tunnel. M. Barnes, the kicker engineer from TRIUMF, is spending a sabbatical year at CERN assisting in the kicker commissioning as well as working on other CERN kicker developments.

TRIUMF personnel continue to assist CERN in the development of the data acquisition boards for readout of beam instrumentation. This is primarily firmware development and transfer of design information to CERN personnel as the series production of 1850 modules will take place at CERN.

Beam dynamics studies of beam-beam effects in the LHC continue to be supported by a TRIUMF physicist. Particle tracking studies require considerable computing effort and this has taken place using the BOINC network (Berkeley Open Infrastructure for Network Computing), where calculations are carried out on thousands of personal computers worldwide that join this network.

The LHC schedule still calls for a cold test of an octant of magnets to take place in late 2006 followed by a beam test through the octant. First collisions are scheduled for July, 2007.

BEAM DYNAMICS

Beam Optics and Stability

The beam-beam effect is an electromagnetic coupling between counter-rotating bunches of protons as two beams meet and cross in the collision regions, or interaction points (IPs) as they are called. There are two types of beam-beam effect: incoherent (single-particle to bunch) and coherent (bunch to bunch). TRIUMF provided support to the LHC for the study of both these destabilizing interactions.

Tracking of the LHC at collision

In 2005, particle tracking studies of the LHC machine at collision became an important part of the CERN beam dynamics effort. The objective is to compute the dynamic aperture in the presence of magnet errors and incoherent beam-beam interactions, optimize the machine working point on the tune diagram, and to study different bunch crossing schemes. In the LHC, the two beams cross at an angle at the four IPs, hence one has to make a choice of crossing plane in each of the two high luminosity experiments, CMS and ATLAS. At present, preference is given to an alternating scheme, i.e. horizontal and vertical crossing planes.

The simulation model, completed in mid 2005, included head-on and long-range beam-beam interactions and corrected field imperfections applied to the interaction region quadrupoles; gradient and misalignment perturbations were excluded. By late 2005, based on million-turn tracking of single particles, the results of tune scans were accumulated for both the nominal and pacman bunches. Our analysis of the dynamic aperture and border of chaos enabled us to identify and explain the advantages of horizontal-vertical versus horizontal-horizontal crossings. In addition, the effect of the beam-beam force was compared with that of corrected field errors. No better tunes were found in either crossing scheme, but a new area has been identified for future scans.

The total number of batch jobs launched from TRIUMF, in support of these studies, was equivalent to four years of 1 GHz CPU time; these jobs were performed mainly on the BOINC network. The BOINC system joins several thousand personal computers world wide, and is at the moment used primarily for LHC beam-beam studies.

Coherent beam-beam effects in the LHC

This study of beam-beam interactions in the LHC seeks to identify potentially unstable coherent modes of bunch oscillation. Extensive studies have been performed at CERN using simulation codes developed with TRIUMF's help, in implementing a hybrid fast-multipole model of beam-beam forces, and in extending the model to 3 dimensions in a parallel-computing environment.

This year, the prototype of a new large-scale beam-beam simulation was developed by CERN, and we formed initial plans for a further TRIUMF contribution in 2006, consisting of adapting the code for parallel computing, with testing, benchmarking and further development for one or more parallel architectures. The new software is intended, eventually, to simulate "all collisions" in the LHC, incorporating all circulating bunches in the two beams and all four IPs. To enable this scale of simulation we shall prepare, in 2006, a proposal for access to a massively-parallel system in Europe, and will likely also utilize WestGrid's facilities which feature a variety of cluster and shared-memory architectures.

Nonlinear beam dynamics code: LieMath

The Truncated Power Series Algebra (TPSA) is an advanced technique used to create and analyze high-order accelerator maps. It serves as a basis for beam-optics software such as COSY Infinity and MaryLie. LieMath is a package of Lie-algebra tools written at TRIUMF in the scripting language MATHEMATICA. During 2005, the speed of execution of LieMath was increased significantly by equipping it with TPSA. Further, the capabilities of LieMath were enhanced by the addition of an optimization module and interface with MAD. Among the potential applications are the LHC, FFAGs and the Linear Collider damping ring and interaction region. In 2005, the LieMath package was included in the Web-based dynamic accelerator-physics software repository (CARE HHH European Network).

CONTROLS AND INSTRUMENTATION

LHC Orbit System Components

Firmware development for the DAB64x Rev 0.0 VME module continued throughout the beginning of 2005. In April, two members from the Electronics Development group travelled to CERN to test the DAB64x firmware functions and check for hardware compatibility with the new VME64x acquisition system. DAB64x hardware tests were completed successfully for the Wide Band Time Normaliser (WBTN) mezzanine, the Individual Bunch Measurement System (IBMS) mezzanine and the Beam Loss Monitor (BLM) mezzanine. A further revision of the DAB64x module was required to provide additional hardware support for the IBMS and BLM mezzanines. Ten DAB64x Rev 1.0 modules were manufactured and assembled at CERN; two modules were sent to TRIUMF for firmware development. Minor additional printed circuit board modifications were requested by CERN to improve test coverage of the JTAG test jig during module manufacture. Two DAB64x Rev 2.0 modules will be delivered to TRIUMF in January, 2006. Production of 1850 DAB Rev 2.0 modules is scheduled for completion by December, 2006.

KICKER MAGNETS

The completion of the LHC injection kicker system was the culmination of 10 years of effort by the TRIUMF Kicker group. This included prototype design, final design fabrication and extensive high voltage testing at TRIUMF as part of a Canadian contribution to CERN LHC. Six RCPS and nine PFNs, together with associated switch tanks, and dump switch terminating resistors have been built at TRIUMF and all have been tested at high voltage (60 kV) to ensure that the performance is within specification. Each of two LHC injection kicker magnet systems must produce a kick of 1.3 T.m with a flattop 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 pulse forming networks (PFN) and two resonant charging power supplies (RCPS).

The series of 9 PFNs has been built to a high precision and successfully tested at TRIUMF. The high voltage pulse measurements are in excellent agreement with both the low voltage measurements and with PSpice predictions. The standard deviation in the relative field for the 9 PFNs, measured over 18 months, is 0.11%, indicative of the long-term stability as well as the precision of the fabrication. The measurements show a flattop field ripple with a standard deviation of less than 0.16%, over the full flattop of the pulse. Such high precision PFNs ($\pm$0.16% flattop on pulse), designed at TRIUMF, are a world first: the design was based on extensive, detailed, computer modelling. The best previously obtained result at CERN was a $\pm$1% flattop with a PFN that could be manually trimmed. The prototype worked the first time as designed with no adjustments or tuning required. The summary of the final high voltage measurements on all of the PFNs was presented at the 2005 Particle Accelerator Conference in Tennessee, in May [Barnes, Wait and Ducimetière, *High voltage measurements on nine PFNs for the LHC injection kicker systems*, (in press)].

There have been 6 shipments from TRIUMF to CERN by ocean freight and the final shipment arrived in CERN in September. Final testing of these systems has commenced at CERN and installation of components into the galley beside the LHC tunnel has begun. The total value of the 6 shipments to CERN is about $4 million.

Gary Wait has retired and Michael Barnes is spending a sabbatical year at CERN with the LHC kicker group and is studying the beam impedance of the LHC kicker magnets. Figure 333 shows the completed PFNs at TRIUMF ready for shipment to CERN.

Fig. 333. Completed PFNs at TRIUMF ready for shipment to CERN.

Because of the high beam intensity in the LHC a beam screen is placed in the aperture of the kicker magnets. This screen consists of a ceramic tube with conducting stripes on the inner wall. The stripes provide a conducting path for the image current of the beam and screen the ferrite against Wake fields. At one end the stripes are directly connected to the standard, metallic, LHC vacuum chamber and at the other end they are capacitively coupled to the vacuum chamber. The stripes initially foreseen gave adequate low beam impedance, however, inter-stripe discharges were observed during pulsing of the kicker magnet at PFN voltages of less than a quarter of the nominal voltage. A photomultiplier tube was used to observe the discharges. A new development program has therefore been undertaken at CERN which includes detailed modelling of the kicker magnet using both Opera2D and PSpice. Various options for the stripes have been considered and appropriate resistivity of materials chosen for field rise-time purposes. This procedure has eliminated several options as the high resistivity of material required would result in excessive beam impedance. A ceramic beam pipe with 24 slots (Fig. 334) has been manufactured and conductors successfully inserted. In comparison with the original ceramic beam pipe with conducting stripes painted on the inside surface, the slotted structure increases tracking distance between conductors and allows the conductors to be radiused (the painted stripes have a sharp edge). An alternative design under consideration is to sputter a high resistance conducting surface over the original, painted, stripes. An abstract concerning this work has been submitted to EPAC 2006.

Detailed analysis of the simulation results has shown a possible anomaly between the Opera2D predictions and those obtained from a 3D PSpice model which is itself derived from Opera2D results. The anomaly is not yet understood and detailed measurements are required to determine which of the models is most appropriate.

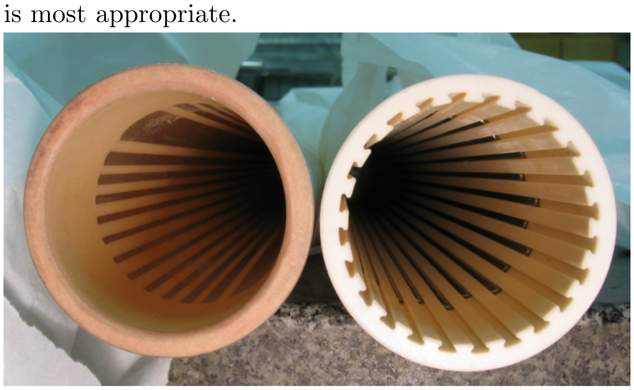

Fig. 334. Left: original ceramic beam pipe with stripes painted on inner surface. Right: new, slotted, ceramic beam pipe with conductors in slots. Photo courtesy of Noel Garrell (CERN).

The slotted ceramic beam pipe, with conductors, is presently being baked out and will be ready to insert in the aperture of the LHC injection magnet early in 2006.

CERN has previously developed a double shielded inductive probe for performing differential measurements of the field in the aperture of kicker magnets. The inductive probe consists of 5 PCB elements: each element is 65 cm long. An equivalent circuit of the MKI measurement probe has been derived and checked against the measured pulse response of the actual MKI probe. The equivalent circuit of the probe in the MKI magnet has then been used to optimize the probe termination, at both ends, and the value of resistors between the shields and ground. The dc resistance (2 Ω) of the measurement loop of the probe introduces a measurement error of 2.8% in the absolute magnitude of the field. This can be corrected for by scaling the measured field by 1.028. Low inductance terminations will be constructed early in 2006 and then the probe will be used to perform detailed measurements on the MKI magnet, with and without the ceramic beam pipe inserted. The results of the PSpice simulations have, where possible, been verified by using the MKI probe to make measurements on an existing MKD kicker magnet. Similarly conclusions drawn from the simulations concerning the differential impedance of the measurement loop of the probe have been verified against the results of previous trial and error terminations on similar probes. A draft technical note has been written.

A five-turn continuous extraction system is presently used to transfer the proton beam from the CERN Proton Synchrotron (PS) to the Super Proton Synchrotron (SPS). Unavoidable losses of about 15% of the extracted beam and poor betatronic matching with the receiving machine affect the present approach, which is based on cutting the filament beam into 5 slices using an electrostatic septum. For CERN Neutrinos to Gran Sasso (CNGS) the beam intensity has to be increased by a factor of 2: the present losses are a serious obstacle to an intensity upgrade of the PS/SPS Complex. To overcome these difficulties, a novel multi-turn extraction (MTE) technique has recently been proposed. In the MTE scheme, beam is separated into a central beam core and four islands by means of elements such as sextupoles and octupoles. Each beamlet is ejected using fast kickers and a magnetic septum. For the kickers of the MTE scheme, two new pulse generators plus one spare are required, each containing a lumped element PFN of 12.5 Ω, 80 kV and 12.6 μs. To achieve a cost-effective design, 15 Ω transmission line kicker magnets are initially to be reused from a previous project, hence the PFN characteristic impedance deliberately mismatches that of the magnet to allow a higher maximum available kick. The PFN design has been optimized such that undesirable side-effects of the impedance mismatch, on kick rise-time and flat-top, remain within acceptable limits. A draft technical note has been written and an abstract is to be submitted to the 2006 International Power Modulator Conference.