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UNDER A CONTRIBUTION FROM THE
NATIONAL RESEARCH COUNCIL OF CANADA

APRIL 1999

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

By the end of 1997 a large amount of equipment had been delivered to CERN in time for the 4 month shutdown at CERN for the PS (Proton Synchrotron) Conversion and the PSB (Booster) energy upgrade. This equipment included: 36 transfer line power supplies and 8 high voltage supplies produced by Inverpower Controls; several smaller supplies and control boards produced by other firms; 5 large rectifier transformers for the Booster main magnet supply made by Ferranti-Packard; a 20 MVar static var compensator assembled by GEC-Alsthom in the UK with some components made in Canada; 7 water-cooled BT quadrupoles, 5 DVT steering dipoles and 3 larger BVT bending magnets for the PSB to PS transfer line assembled and field mapped at TRIUMF; and ferrite rings for the PSB cavities and several designs of higher order mode dampers for the PS cavities.

This equipment was installed and commissioned at CERN and the collaborators at both TRIUMF and CERN were pleased to find that the equipment worked reliably at start-up in March, and has given little trouble during beam operations in 1998. There are still a few active tasks related to the PS Conversion project. A second order of 100 kW and 250 kW transfer line power supplies was placed in October. These supplies will be designed and built by an alliance of three firms in Ontario, I.E. Power, Inverpower Controls and DPS. Delivery of the first 100 kW unit is scheduled for April, 1999. Two other tasks are the design and fabrication of a prototype fast blade scanner and 4 sets of X and Y fast wire scanners for the PS Booster. The fast blade scanner has been built and is being tested at TRIUMF. Tuning of the servo motor and blade mechanism is proceeding, but achieving the fast response with smooth motion of the blade is proving difficult. The design of the fast wire scanners is based on a CERN design for the PS and this work has started.

The production run for the front-end electronics for the SPS beam position monitors was completed during the year. First, a run of 40 of the 200 MHz modules was completed and these were tested on the SPS during the summer. Then the remaining 245 modules, with some minor improvements, were assembled by a local firm and sent to CERN before the end of the year. A problem with the TSM (timing surveillance modules) produced by TRIUMF was resolved and two batches of these modules were built and sent to CERN during the year.

The prototype twin aperture quadrupole manufactured by ALSTOM Canada (previously GEC-Alsthom) in Quebec was completed and shipped to CERN for testing. Magnetic field measurements show that the harmonic content is larger than desired and is correlated to the physical measurements of the pole gaps. Even tighter assembly tolerances than originally specified will be required. A number of improvements have been proposed by CERN, TRIUMF and ALSTOM engineers for the series production. The production of a second set of prototype coils with fewer splices is under way and a contract for new punching dies for the improved lamination shape will be let in January, 1999.

The fabrication of the prototype 60 kV resonant charging supply for the LHC injection kickers was completed at TRIUMF and the supply sent to CERN for testing with a prototype pulse forming network (PFN) built at CERN. High voltage measurements carried out in August confirmed the design predictions from PSpice, and the group has now moved to the series production. Five power supplies, 9 PFNs and 20 thyratron switches are to be manufactured by TRIUMF over the next few years.

The collaboration with the PS radio frequency group is essentially complete. All of the required higher order mode dampers and filters for the 40 and 80 MHz cavities were delivered to CERN. One of the prototype high voltage supplies was returned to Inverpower for retrofitting to the later design.

In the beam dynamics area work has continued on studies of dual harmonic acceleration in the PS Booster, with participation in machine development runs at CERN. Space charge was added to the ACCSIM code along with several other improvements. The task to study impedances of the LHC components continued with calculations and measurements on kickers, and calculations of the effect of beam screens and pumping port shields.

The optics of the LHC cleaning insertions to provide efficient momentum and betatron collimation have been settled. The new solution replaces some of the warm quadrupoles with cold quadrupoles, and to arrange for one of the warm quadrupoles in each of the four central sets to be powered for symmetric focusing. This reduces the number of twin aperture quadrupoles to 48 plus spares. The task of generating a computer model to simulate beam behaviour in the SPS and LHC for tune control has made good progress and beam measurements on the SPS and HERA at DESY have been used to validate the code.

The first meeting of the LHC Board was held at CERN at the end of March. This Board has representatives from non-member states who are contributing to the LHC (Canada, India, Japan, the Russian Federation and the USA), along with representatives from France and Switzerland who are making special contributions as host countries.

A second contribution to the LHC is included in the request for TRIUMF funding for the next five-year plan (2000–2005). This request would allow completion of the series production of twin aperture quadrupoles, the LHC kicker work and power supplies for the warm magnets in the cleaning insertions.

BEAM DYNAMICS

Second Harmonic in PSB

Dual harmonic acceleration

The PS booster has two rf systems. The fundamental rf is synchronized to the beam fundamental, while the second harmonic may be locked either to: (a) the beam or (b) the fundamental rf. In 1997, operating with harmonics 5 and 10, the longitudinal instability occurring when type (b) control is used was diagnosed as a sextupole mode (see Fig. 153), with growth rate almost independent of beam current. The dual-harmonic confining potential causes bunches that exceed a critical length to lose Landau damping of their within-bunch oscillation modes, thus making them susceptible to being driven by the low-level rf system. The relative amplitude and phasing of the two rf systems varies widely during the acceleration cycle, and a computer program BTF-FAST2 was written to compute the corresponding beam transfer functions (BTFs) for amplitude and phase modulations. In fact, there are two BTFs – one from fundamental rf to beam (B_{11}) and another from second harmonic to beam (B_{12}).

Measurements during the year showed that the instability survived the migration from harmonics 5 and 10 to harmonics 1 and 2, and from analogue to digital control and the 5 times smaller delay-induced phase lags; they also confirmed that switching to type (a) control is still sufficient to avoid the instability. Based on a mixture of numerical modelling of the beam and analytic modelling of the low-level rf systems, it was realized that the stabilization mechanism arises from a quirk in the control topology. As is well known, a feedback system with large gain and 180° phase lag is unstable. With type (b) control the beam response is $B_{11}+B_{12}$, whereas with type (a) the beam response is roughly $B_{11}/(1-B_{12})$. In this latter case, the B_{12} BTF acts as a phase-advance network where the gain of the composite transfer function is large, thus avoiding the 180° lag condition.

Acceleration of hollow bunches

The peak transverse space-charge tune-shift can be reduced if the longitudinal charge density is reduced. One means to achieve this is dual-harmonic rf; an alternative or complementary procedure is to create bunches with a hollow distribution in longitudinal phase space. If high-harmonic empty buckets are decelerated into the core of an unbunched coasting beam, and this is subsequently captured into a normal rf bucket, then the result will be a hollow beam. Preliminary tests, performed in the early summer with low current beams, indicated the procedure to be feasible as demonstrated in Fig. 154.

Space-charge forces complicate the procedure: transverse forces limit the dwell time and longitudinal forces modify both the high-harmonic empty buckets and the fundamental-frequency full ones. Numerous computer simulations of the beam dynamics with an improved space-charge algorithm but no rf control loops indicated that the hollow structure could be maintained, provided the beam current is not too great. These simulations also showed that fine-tuning

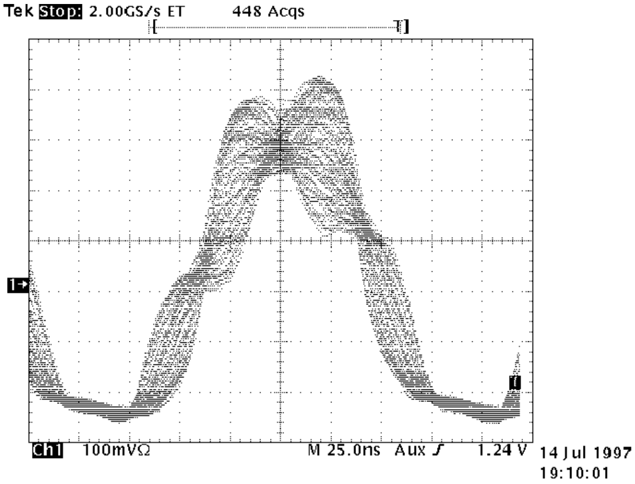

Fig. 153. Overlays of sextupole oscillation time series.

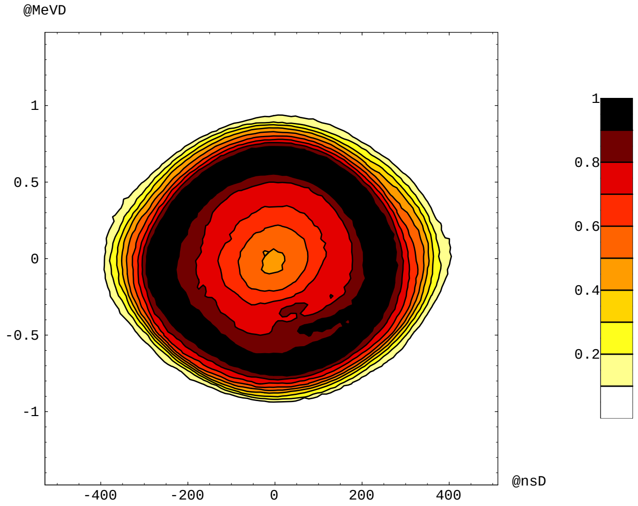

Fig. 154. Tomographic reconstruction of phase space.

of the empty bucket deposition becomes difficult at high current.

Experimental studies in the fall confirmed these predictions and also indicated a further problem: an instability occurs when hollow bunches are accelerated in dual-harmonic buckets. The dominant oscillation mode seems to vary with time, and the oscillation can be tamed temporarily by running the second harmonic rf open loop.

Measurements later in the year concentrated on using the beam transfer function measurement (BTFM) to carefully specify the initial beam conditions and precisely target the central momentum of the empty high-harmonic buckets compared with that of the beam. A procedure was devised that allows $h = 15$ bucket deposition followed by either a fast BTFM or capture into $h = 1$ buckets during a 12 ms flat-bottom. Despite these improvements, repeatable and reliable capture and acceleration of a high-intensity beam was still elusive. A large amount of experimental data was acquired and awaits quantitative analysis.

Injection and Collimation in the PSB

This task involves the development and support of the ACCSIM multi-particle tracking and simulation code. This year efforts were concentrated on implementing an improved model of transverse space-charge, going beyond the existing DQ package, which is able to give very efficient estimates (and simulations) of space-charge tune-shifts, but which is not fully self-consistent in its tracking of the macroparticles ensemble.

A survey was conducted of the common field-solution and tracking (integration) techniques. These come from the plasma physics realm and have been applied to linacs and beam lines but seldom to rings, where the ensemble must be tracked for many revolutions. Moreover, the popular FFT-based field solvers do not lend themselves well to beams with a large and growing halo, a feature of concern for intense-beam multi-turn injection schemes.

A field solver was developed which is a hybrid of fast-multipole (FMM) and particle-in-cell (PIC) techniques. It can accommodate charge distributions with any number of halo particles at arbitrarily large amplitudes, and at equivalent spatial resolutions it is competitive in speed with FFTs. ACCSIM tracking of K-V beams in test lattices with this method produced the expected fields, single-particle tunes, and envelope tunes. A paper on this work was presented at the Shelter Island Workshop on Space-Charge Physics in High Intensity Hadron Rings.

Other additions to the code were: a generalized rf cavity element allowing arbitrary (non-integer) harmonics and phases; rf voltage plotting; interactive injection steering; and import and export of particle ensembles, allowing generation and stacking of "beamlets" at arbitrary locations.

Beam Stability

LHC abort kicker

The broadband impedance of the abort kickers has been investigated using coaxial wire measurements and numerical simulations, especially the screening effect of a thin metallized layer on a ceramic pipe around the beam. The purpose of the metallic layer is to reduce the impedance by shielding the beam from the kicker components, and also to reduce the heat load on the ferrite; at the same time the layer must be thin enough to be transparent at low frequencies so that the magnetic pulse from the kicker can penetrate it.

The measurements showed that a 0.1 μm-thick layer of copper (or 0.4 μm-thick layer of chromium) with a sheet resistivity of 0.1 Ω/square can effectively shield the kicker environment from electromagnetic fields generated by the LHC bunches at frequencies from 0.5 MHz to 1 GHz (the most dangerous range), even though the skin depth of copper at 1 GHz is 2 μm and some theories predict that a layer that thin should be transparent in this frequency range. It has been found that, provided there is good electrical contact between the beam pipe and the conducting layer, the image current from the beam pipe will almost entirely pass through the layer. The total impedance of the kicker is therefore determined by the impedance of the conducting layer, which normally is very small (less than 1 Ω) and is virtually unaffected by the kicker elements such as magnet coils, cables, etc., located outside the pipe.

Theoretical and experimental work related to the screening effect of a thin metallic film were discussed at a special mini-workshop held at CERN in November. The measurement results led to rejection of a theoretical model for the screening efficiency of a metallized ceramic pipe which has been widely used in kicker designs for more than a decade. A new theoretical model has now been developed which explains both the experimental results and the failure of the old model.

LHC injection kicker

The longitudinal impedance of the LHC injection kicker has been measured using the coaxial wire method and analysed using MAFIA 3D simulations. The measurements focused on the properties of ferrite specimens, which then were used to calculate power losses in the kicker.

LHC beam screen

The new "ribbed" design for the LHC beam screen, intended to better absorb synchrotron radiation and avoid promoting electron cloud instability, has been found to make a relatively small (but not negligible) contribution to the total LHC broadband impedance budget.

SPS pumping ports

3D MAFIA impedance calculations of the proposed shields for the roughly 800 SPS pumping ports (thought to be the major contributors to SPS impedance) have been made in an attempt to optimize their designs.

Beam Optics and Collimation

This year has seen the successful determination of optics which will allow efficient momentum and betatron collimation in the LHC cleaning insertions (IR3 and IR7 respectively).

The optics solutions available in early 1998 required too much strength from the warm quadrupoles in the straights (for which the field quality was rather uncertain at maximum excitation) and from the trim quadrupoles in the dispersion suppressors, especially after a 1997 redesign introduced special cold quadrupoles longer than the standard ones in the arcs, and shortened the trims from 1.7 m to less than 1.3 m. Moreover, the maximum achievable normalized dispersion $D_{xn} \equiv D_x/\sqrt{\beta_x}$ at the primary collimator in IR3 was 0.16, just marginal for protecting the arcs from off-momentum halo protons. These optics were somewhat constrained by the focusing-defocusing quadrupole antisymmetry about the midpoint of the insertion (Fig. 155, top) imposed by the use of twin aperture quadrupoles wired so that if one beam were focused the other would be defocused.

The basic feature of the new solutions is to relax this constraint, increasing the optical asymmetry and giving improved performance with reduced overall focusing strength. To achieve this, we suggested converting some of the 3 m long modules making up each warm quadrupole so that they focused both beams (realized in practice by changing the coil connections).

The current arrangement, adopted for LHC version 6 (Fig. 155, bottom), has one of the new "symmetric" focusing modules (black) in each of the four central quadrupoles. With such a set-up, a peak normalized dispersion 0.2–0.24 (depending on the LHC working point) can be achieved (Fig. 156), and no modules need work near their top field.

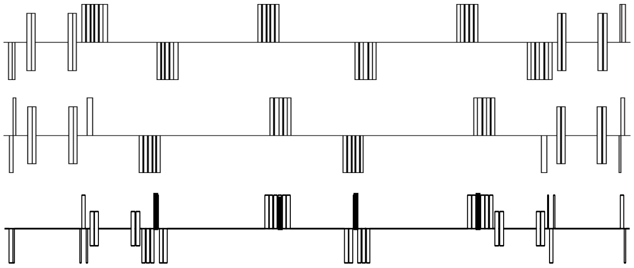

Fig. 155. Evolution (from top to bottom) of the IR3 straight section.

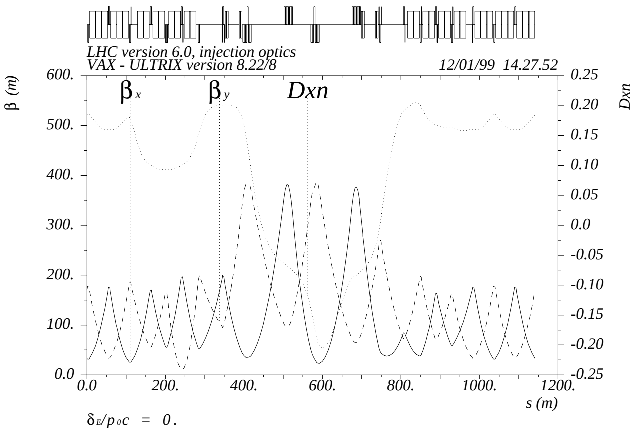

Fig. 156. Lattice functions for IR3 in LHC version 6 (straight section and both dispersion suppressors).

It may also be noted that the dispersion suppressor quadrupoles have reverted to standard length, with 1.15 m long trims, and that the outermost warm quadrupole has been replaced by a standard cold one (to save space), requiring the dogleg magnets to be shifted to its midpoint side to make the cryogenic connections easier. The quadrupole hardware needed for the two straights is $2 \times 4 \times 6 = 48$ warm modules (of which $2 \times 4 = 8$ are symmetric), and $2 \times 2 = 4$ cold (trim+quadrupole+trim) groups replacing 24 warm modules.

Other tasks completed include: implementation of the new IR3 and IR7 lattices into the LHC database; tuning for different LHC working points; and development of the code "Distribution of Jaws" with the aim of studying how collimation is affected by misalignments of the collimator jaws and quadrupoles and by orbit errors left after simulated correction by DIMAD.

Simulation Tool for LHC/SPS Tune Control

An important issue for LHC operation will be the continuous monitoring and correction of the betatron-tunes and chromaticities in the presence of time-varying magnet non-linearities. In collaborating with CERN's efforts to develop a system to do this, TRIUMF is generating a computer model to simulate the proton beam's behaviour, while CERN looks after the control side. The FASTMAP suite of tools has therefore been written to facilitate high-speed tracking using COSY-generated maps, and to customize the maps to at least 12 tuning parameters ("knobs") in addition to the six kinematic variables. FASTMAP has also been interfaced with a Measurement front end capable of simulating measurements of tune, chromaticity and coupling by a variety of techniques. Using FASTMAP involves the following steps:

1. TWISS2COSY converts SPS and LHC lattices from MAD8/9 file format into a FOX file executable in COSY.

2. COSY is used to obtain a set of parameterized maps. As memory and performance limitations in COSY make it difficult to work with more than 2 or 3 free parameters for a 6th order map, the requirement for at least 12 free parameters means that several maps have to be produced.

3. MAPMERGE combines all the parameterized maps into one table (a map-like object that depends on all the parameters). Note that the output file is not a "map" in the strictest mathematical sense unless all cross-coefficients are supplied.

4. The FMLIB objects are used to read the MAPMERGE output, evaluate parameters in the map, collect coefficients, and perform the particle tracking.

An important feature of the TWISS2COSY converter is its ability to identify repetitive parts of the lattice and factor these out to produce the shortest possible representation. The maps for repetitive sequences can then be pre-computed and used repeatedly in the final stage of calculating the map for the whole ring, with a considerable saving in computer time.

The advantage of tracking with FASTMAP rather than COSY arises from a reduction procedure in which, prior to tracking, numerical values are substituted for symbolic parameters, allowing coefficients of like-order kinematic monomials and polynomials to be collected, so that potentially very large maps collapse to 6th order in the six kinematic variables.

In order to validate FASTMAP the following sets of measurements were completed at the SPS:

1. Emittance growth. These measurements were performed with 26 GeV lead ions from the main SPS cycle. The beam was displaced from the closed-orbit by a kicker, resulting in filamentation due to the amplitude dependence of the betatron-tune, and eventually an increase in the rms emittance.

2. Betatron-tune. The tune was measured as a function of the main quadrupole strength, using the 26 GeV proton beam of the Machine Development cycle.

3. Chromaticity. The SPS lepton cycle was used to study the effect of chromaticity changes on the betatron-tune spectrum, by varying the sextupole strength and observing the change in amplitude of the synchrotron sidebands with respect to the main peak. Lepton maps were computed for this case.

For all three measurements the experimental data were in good agreement with the FASTMAP simulations, so we have concluded that the model correctly describes these features. As the quadrupole and sextupole strengths are parameterized quantities in FASTMAP, their measurement provides an important test of FASTMAP's use of parameterized maps and the correct representation of the lattice by them. The results also allowed us to calibrate the kicker, quadrupole and sextupole strengths in terms of their parameterized values.

FASTMAP has also been used in support of experiments on HERA at DESY to test a procedure for measuring LHC chromaticity by analyzing a beam's head-tail motion. The measurements confirmed FASTMAP predictions and made it possible to test new hardware and algorithms. In particular, it was shown possible to excite the beam sufficiently with a chirped pulse.

CONTROLS AND INSTRUMENTATION

Fast Blade Profile Monitor

The fast blade scanner (FBS) is intended for destructive diagnosis of the betatron amplitude distribution of charged particles in the CERN PS Booster by measuring circulating beam current versus blade position. The device accelerates from rest to 5 m/s and decelerates to a stop in 50 ms (moving a distance of 25 cm) while recording its position with 0.1 mm accuracy. The FBS will complement measurements made with wire scanners.

The two Y-shape arms carrying the blade mounting are actuated through a pivot-bellows mechanism which in turn is driven by a bell-crank double linkage. The principal mechanical items (servo motor, driver amplifier and motion controller) arrived in 1997 and were bench tested with a simple dummy load. Assembly of the blade mechanism was delayed until the summer, pending arrival of several sets of precision bearings. During the fall fabrication of the vacuum box and stand progressed swiftly, but e-beam welding of the beam-pipe bellows proved difficult and parts had to be delivered from CERN. Testing and tuning of the blade mechanism and controller progressed in parallel, but very slowly. The blade assembly appears to have a mechanical resonance and tuning of the system for fast response is not compatible with damping of that resonance.

During December, it was realized that the proprietary controls and acquisition hard/software were inadequate for the stringent timing accuracy demanded by the position-acquisition specification. In response, it was determined to separate control from acquisition and build a VME-based system around digitizing and memory components borrowed from CERN. In addition supervision of the motor controller was moved from a PC to a VME host.

Software was written under the VXworks real-time operating system for several VME devices. This included basic driver support and a program file loader for the Galil 1380 motor controller, control and data acquisition drivers for the CERN DPM memory module, and control and data acquisition drivers for the INCAA VD71 transient digitizer. In order to simplify the development work on the blade scanner, a graphical user interface was developed by interfacing these drivers to EPICS.

In parallel, work on building remotely controllable breakers for the power supply, installing safety interrupts and fail-safe break progressed swiftly. It is anticipated to test the VME-based control in February, 1999, and complete tuning of the FBS assembly in March, 1999.

Fast Wire Scanner

The fast wire scanner provides a non-destructive measurement of horizontal or vertical beam profiles by rapidly moving a wire across the beam and using downstream scintillators to measure the beam scattered by the wire. A design exists for the PS and this design must be modified for operation in the four rings of the PS Booster. A TRIUMF designer visited CERN in July to learn about the new requirements and design work was started towards the end of the year. The plan is to build a first prototype by March, 1999, and after approval from CERN, produce 9 more scanners, 4 horizontal, 4 vertical and a spare, for installation during the winter 2000 shutdown.

Upgrading SPS Orbit Observation System

The 240 front-end electronics for beam position measurement in the SPS are to be replaced with new compact, modern modules designed at TRIUMF during 1997. The modules consist of a variable phase-shifter, 200 MHz band pass filters and a calibration unit. In May, 1997, CERN asked for the delivery of an initial batch of 40 by February, 1998 and a further 240 modules by November, 1998 with delivery starting in September. These large production runs, with their very demanding tolerances for phase matching and low insertion loss, were a significant achievement and the outcome of many incremental improvements in the components, the manufacturing/assembly process and the quality assurance procedures.

Initial batch 0917/1 modules

Most parts for the run of 40 modules arrived by January and were forwarded to Link Technologies for assembly. However, the filters from the Microwave Filter Company were delayed due to a problem with silver plating. In February, most of the module construction, including automated parts placement, soldering and assembly was satisfactorily completed by Link Technologies. The modules were finished at TRIUMF by attaching the rf hybrids, phase shift capacitors, filters and precision-length internal cables. Two testing programs were written for the HP8753D network analyzer which plays back pre-recorded sequences of steps to set up tests and make measurements. Some electronics were constructed to allow the analyzer to control the mode and phase shift of the module being tested. In this way, the time to test and document a module's performance was reduced from hours to minutes. A CERN engineer visited TRIUMF in February to help with quality assurance, and the TRIUMF engineer responsible for this task visited CERN in July to work on calibration of the new MOPOS with the 40 modules installed in the SPS (see Fig. 157).

Much was learned from the first production run of 40 modules and several changes were made to the design. M/A-Com quadrature hybrids were found to be more consistent in their SWR than the Olektron hybrids, and were substituted throughout. The filters used for the 40 modules were not as precisely matched as desired; and 11 filter pairs were rejected. Two manufacturers were asked to build a similar filter but using a precision-machined aluminum casing in place of a folded brass sheet. Lorch responded with greatly improved filters costing twice that of the original, and Microwave Filter failed to meet the May deadline for producing a prototype. The anticipated savings in time, in not having to adjust the substitute filters, and their impeccable performance were deemed sufficient reasons to place the order with Lorch. Link Technologies proved themselves capable and resourceful and it was decided to have them attach all the components, make the phase matching cables and run the module test program.

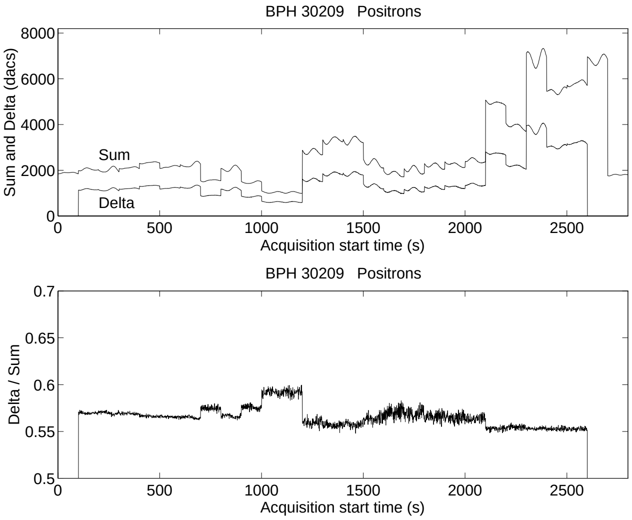

Fig. 157. Closed-orbit (at one location) versus turns in SPS; upper figure is sum & difference; lower figure is difference/sum.

Series production 0917/2 modules

Most of the parts for the further 245 modules were delivered by June ready for sorting into kits. However, delivery of two critical components had to be carefully staged. The customized quadrature hybrids arrived in allotments spanning July to September. The 245 filter pairs in machined aluminum cases arrived in allotments during August and September. The printed circuit cards were ordered last, and the small rf shields and front panels were machined locally. The first pair of improved filters was delivered to CERN in August and tested on-line with proton and lepton signals. Results were favourable and the order for 245 filter pairs was increased to 285. During the summer Link Technologies was bought by US-based Aimtronics.

The automatic test set-up, demonstrated at CERN in August, was later modified at TRIUMF to suit the network analyzer's available memory. Tune up sequences were added to allow the Aimtronics technicians to cut the internal cables to length for phase matching and to adjust the variable capacitors to centre the phase adjustment range. The tests consist of filter performance, the two tuning procedures and a final test of the complete module, with thorough documentation at all stages.

By September the first 100 modules were assembled and the internal tuning and matching of the first 5 finished modules were tested at TRIUMF and found to be excellent. The production run then moved into full swing: by November, 151, and by December, a total of 242 of the 0917/2 calibrator modules had been shipped to CERN. In December it was decided to move the forty 0917/1 series modules to a beam transfer line and substitute them in the SPS with forty more 0917/2 modules. Orders for additional parts were placed in January, 1999.

Design and Production of VME TSM

Early in the year, 5 more timing surveillance VME modules (TSM) were built, tested and shipped to CERN. The empty events problem, which was reported in the previous year, was investigated and found to be caused by distortion of the external clock in some VME crates at CERN. Circuitry enhancements to overcome this problem were designed and tested. Another batch of 8 TSMs was built in November.

POWER SUPPLIES

Booster Transfer Line Power Supplies

All Inverpower Controls power supplies and ancillary equipment were delivered, with installation and commissioning completed by the end of February. The supplies have proven to be reliable and have now been in service for a period of about 8 months. The topology used for the batch 1 supplies was selected as the basis for the design for the dipole supplies which were required for batch 2.

After some delay, due to other commitments of the PS/PO group, specifications for the batch 2 supplies were generated and sent out to tender in the summer. Approval for purchase of the batch 2 supplies was received in October, with delivery aimed for installation during the spring 2000 shutdown at CERN. The contract was awarded to the alliance of I.E. Power, Inverpower Controls and DPS. Design reports for the 100 kW and 250 kW supplies have been forwarded to CERN, with construction of the first 100 kW unit scheduled for the beginning of 1999.

Booster Magnet Power Supply Transformers

The 5 new Ferranti Packard transformers for the booster main magnet power supply were installed and commissioned successfully in January. Figure 158 shows one of the transformers in location.

Reactive Power Compensator

The new static VAR compensator supplied by GEC Alsthom was installed and successfully commissioned in March (Fig. 159).

MAGNET DEVELOPMENT

Transfer Line Magnets

Quadrupole and dipole magnets of four different designs, designed and manufactured by TRIUMF and described in last year's Annual Report, have been installed in the PSB to PS transfer line, except for one BV2 dipole which will be installed in 1999. These magnets have laminated yokes and higher current capability than the solid pole magnets they replace. Two CERN reports, SL-Note-98-052 and SL-Note-98-063, were written jointly by the CERN and TRIUMF

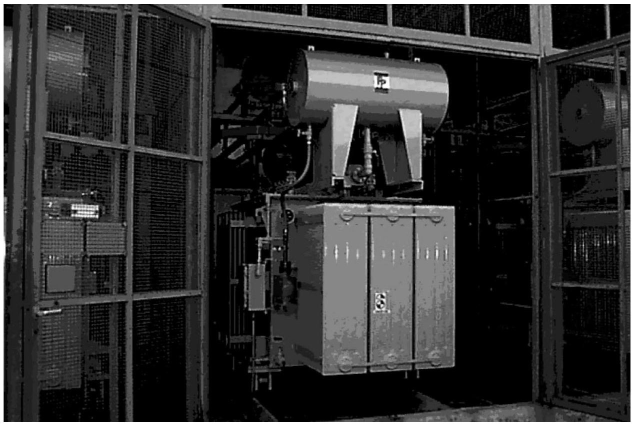

Fig. 158. One of the five large rectifier transformers for the PSB main supply made by Ferranti Packard.

Fig. 159. Static VAR compensator for transient suppression made by GEC Alsthom, UK (40% Canadian content).

collaborators describing the design and parameters of these magnets and the results of the magnetic field measurements.

Cleaning Insertion Magnets

The prototype twin aperture quadrupole manufactured by ALSTOM Canada Inc., arrived at CERN May 7 (see Fig. 160). Magnetic measurements were started in September and discussed at an October meeting between CERN, TRIUMF and ALSTOM. At a low current of 41 A (LHC injection) the low order multipole components are about a factor of 5 too high. The dipole, quadrupole, sextupole and octupole components are respectively 150, 10000, 20 and 20 LHC units. At high current (710 A) they are a bit lower but still very large: 70, 10000, 15 and 15 units.

Fig. 160. The 3 m long twin aperture quadrupole made by ALSTOM Canada Inc.

The field errors do correlate with the dimensions of the pole gaps as measured at CERN with a “Grabnermeter” device. It has now been determined that the production magnets must be assembled with much higher tolerances than originally envisaged. Thirteen methods of improving the design magnetically were identified. The shape of the laminations was fixed in early December. A contract for new punching dies is presently being considered.

A contract was awarded to ALSTOM Canada in July to make new prototype coils with at most 4 splices per coil. These prototype coils are expected to be finished in late February, 1999. Before the series production of the magnets can start CERN must specify more completely the changes they wish to make to the design. CERN is working on purchasing the steel and conductor needed. TRIUMF expects to award the series production contract for the first 25 magnets during the summer of 1999.

KICKER MAGNETS

LHC Injection Power Supply and PFN

A prototype resonant charging power supply (RCPS) was designed and assembled at TRIUMF (Fig. 161). The RCPS has a 2.6 mF storage capacitor bank charged to 3 kV. A gate turn-off thyristor (GTO) 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 being transferred to two 5 Ω pulse forming networks (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 at a repetition rate of 0.2 Hz. An LHC injection system will consist of a RCPS, which has two parallel outputs, to charge two 5 Ω PFNs. The PFN has thyratrons at both ends. 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 DS thyratron is used to control field flat-top duration to be either 4.25 μs or 6.6 μs. The prototype PFN was built at CERN (Fig. 162).

During March acceptance tests were carried out on the prototype RCPS in the presence of CERN collaborators. Tests with an open circuit and a short-circuit

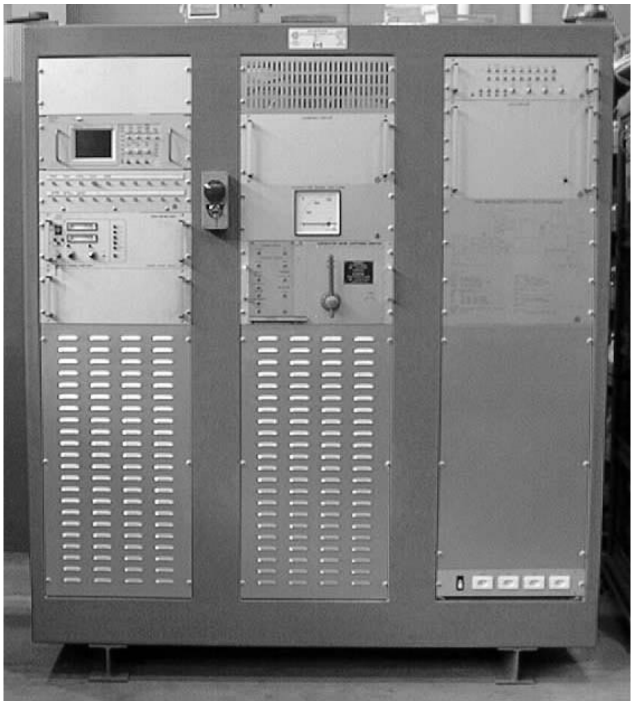

Fig. 161. Prototype RCPS.

Fig. 162. Prototype PFN with capacitors and coil installed.

secondary were carried out. The RCPS was also tested at frequencies up to 0.2 Hz and voltages, on 2 dummy PFN loads, of 66 kV. The measured charge time of less than 840 μs and effective charge time of less than 1300 μs both improved upon the specified maximum values of 1 ms and 2 ms, respectively.

A stability test was carried out on the RCPS for 46 hours of continuous operation. The RCPS was operated at 55 kV and 0.1 Hz and the voltage on one of the dummy loads was measured periodically. The maximum spread in voltages was ±0.085% over two days, whereas the maximum permitted spread is ±1%. At the end of the test, voltages were measured every 10 s and the maximum voltage spread was ±0.03% for 30 pulses (the maximum permitted spread is ±0.1% over 12 consecutive pulses for LHC injection). Measurements taken from a cold start had a maximum voltage spread of ±0.016% for 14 pulses. The RCPS passed all tests.

Low voltage measurements (up to 10 kV) were carried out on the prototype PFN during May. Analysis of measurements indicated that the inductance of each cell of the PFN is approximately 4% greater than predicted. This is now attributed to the coil inductance being high due to the coil tubing being distorted during winding, resulting in an increased mean radius of the coil.

The RCPS was shipped to CERN in June and set up to prepare for high voltage testing of the prototype PFN. High voltage measurements (up to 66 kV) were carried out starting in August. The test circuit did not include a kicker magnet. In addition the second output of the RCPS was connected to a dummy load, which was designed and built at TRIUMF.

A FET-based pulse generator, designed and built at TRIUMF, was used to generate a “known” voltage pulse for calibration purposes.

It is not possible to use the available adjustments in the probe compensation box to meaningfully measure flat-top ripple and post pulse ripple in the ±0.1% region. Thus a procedure was developed to calibrate the high voltage probe and oscilloscope amplifier:

- Use the FET-based pulse generator to generate a “known” waveform. Compensate the probe and store this reference waveform digitally. The compensation at this stage is only approximate;

- Comparison of the reference and “known” waveforms gives the calibration curve (for a given waveform shape), as a function of time, for the probe and oscilloscope amplifier (for a given gain).

Figure 163 shows predicted field for a 33 cell transmission line type kicker magnet. The prediction is obtained by using PSpice to stimulate the equivalent circuit of the kicker magnet using the voltage waveform measured across the MS terminator, for a PFN voltage of 55 kV.

Detailed measurement and analysis of pulse shapes show:

a) the top of the measured voltage pulse was flat to within ±0.3% for the “as designed” PFN, i.e., without any adjustments to the PFN component values.

b) Mismatching the DS terminator resistor by approximately 10%, and measuring the MS terminator voltage, confirms that, for a PFN voltage of 55 kV, the MS thyratron (CX2003) blocked the reverse voltage.

c) The 0.2% to 99.8% kicker magnet field rise time is 834 ns (shown between arrows on Fig. 163), and is within specification (900 ns).

d) The 99.8% to 0.2% kicker magnet field fall time is 2.94 μs (shown between arrows on Fig. 163), and is within specification (3 μs).

e) The kicker magnet field is within ±0.2% during a 4.69 μs flat-top (shown between arrows on Fig. 163).

The LHC injection design requires that the flat-top and post pulse field are flat to within ±0.5%.

In order to fully test the RCPS, a series of tests were carried out where the MS and DS thyratrons were deliberately turned on at times which are known to test the integrity of various RCPS and high voltage components. If the thyratron turns on just after current zero in the GTO the rapid collapse of voltage across the transformer secondary results in a forward dV/dt of approximately 110 V/μs across the GTO. As expected, the GTO was not damaged by this forward dV/dt immediately following current zero. In addition, the GTO had previously been subjected to more severe tests of 160 V/μs.

In subsequent tests the PFN was pulsed at 0.1 Hz for 130,000 cycles. One of the transformer primary connections failed, and the transformer has been rebuilt with mechanical design changes to prevent such an occurrence again.

The combined stability of the RCPS, PFN and MS terminating resistor is such that the maximum excursion of the flat-top of the MS terminator voltage is ±0.035% with the PFN pre-charged to 60 kV.

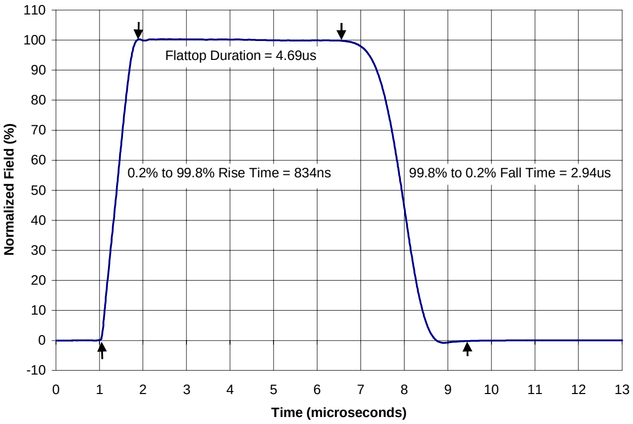

Fig. 163. Predicted field in kicker magnet, derived from measured PFN voltage of 55 kV.

The prototype RCPS and PFN passed their tests. Hence the TRIUMF Kicker group are starting on the series production of 5 RCPS, 9 PFNs and 20 thyratron switch units. Orders for many of the main components, including 3 kV power supplies, storage capacitors, low leakage inductance step-up transformers, filter capacitors, high voltage diodes, and high voltage receptacles have been placed. In addition quotations for 550 PFN capacitors have been received, and 10 sample capacitors have been ordered from the two low bidders. A circuit for testing the sample capacitors has been designed, and is presently being assembled.

RADIO FREQUENCY SYSTEMS

Coordination/Project Planning

Two 40 MHz and three 80 MHz cavities have been built at CERN as part of the preparation of the improvement program of the PS as an injector for the LHC. The 40 MHz cavities provide bunch spacing, while the nominal small bunch length is provided by the 80 MHz cavities. Higher order mode dampers for these cavities have been provided by TRIUMF. Both the second 40 MHz and the third 80 MHz cavities equipped with higher order mode dampers are ready to be installed in the PS. The dampers installed in the first 40 MHz and the first and the second 80 MHz cavities have already been tested with beam in the PS. The dampers have performed as designed and have withstood the full operating voltage of the cavities without any multipactoring, breakdown or heating problems.

40 MHz Cavity Structure

Higher order mode dampers at 260 MHz and 504 MHz were needed for the second 40 MHz cavity at CERN. These dampers were similar to the dampers, which were designed and fabricated at TRIUMF for the first 40 MHz cavity. Two of each kind of dampers were fabricated at TRIUMF and a signal level test was performed at CERN on the second 40 MHz cavity. The design goal of damped shunt impedance of less than 1 kW for the monopole modes was achieved with a damping of about 5% of the fundamental mode. This 40 MHz cavity has successfully undergone rf power tests with these higher order mode dampers installed where a cavity gap voltage more than 400 kV was reached.

80 MHz Structure and HOMs

Four kinds of higher order mode dampers and three high pass filters were required for the third 80 MHz cavity at CERN. A total quantity of seven dampers and three filters were manufactured and assembled at TRIUMF and were shipped to CERN. These dampers were the same as the previous dampers made for the first two 80 MHz cavities (see Fig. 164).

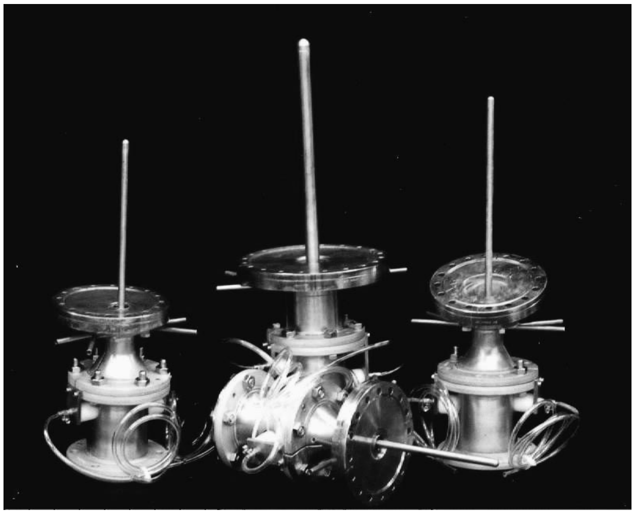

Fig. 164. Higher order mode dampers for the 80 MHz cavities.

High Voltage Power Supplies

Shipment of all power supplies was achieved as scheduled from Inverpower, I.E. Power and Xantrex. Difficulties with the high voltage transformer in the 22 kV prototype resulted in a redesign of the high voltage output stage for these units, with the prototype being returned to Inverpower for retrofit to the latest design. Condensation problems experienced in the summer resulted in supplies being cooled by warmer demineralized water. This subsequently resulted in thermal trips which were solved at CERN by the use of an improved heat sink for the inverter section.