SURVEY AND ALIGNMENT AT FERMILAB

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1. Introduction

The Alignment and Metrology Group at Fermilab has 19 members, of which 11 are field technicians. The other 8 are scientists of various levels. The major activity of the group over the past two years has been the alignment of two new machines, the Main Injector accelerator and the Recycler Ring, which is a permanent-magnet storage ring in the same tunnel. This occupied 55% of the group's effort in 1998, and 30% of the effort in the first half of 1999, even though the tunnel was inaccessible during commissioning half the time.

The group has acquired some new technology recently which has expanded our capabilities. A GSI V-stars photogrammetry system has been purshased, which allows very rapid data acquisition of many three-dimensional points with subsequent off-line computation of the numerical coordinates. On the typically 10 m by 10 m detectors on which we use this system, the accuracy is ~0.1 mm.

A Leica TCR307 reflectorless total station has been purchased which has an advertized accuracy of 3 mm. In our first use of it, we remeasured an array of points which had been very precisely measured with optical tooling and found the rms of the differences to be less than ~0.6 mm. This device is very convenient for objects on which it is difficult to put targets or reflectors and for which the reduced accuracy is allowable.

2. Main Injector

The Main Injector is a 150 GeV accelerator made of conventional magnets which has replaced the Main Ring as the injector into the Tevatron and the source of protons for the antiproton beam target. The purpose of building the Main Injector was to produce a beam with much higher intensity, lower emittance, and lower operating costs than the Main Ring, so as to produce more antiprotons per hour and increase the luminosity of the collider experiments.

The alignment of theMain Injector was completed in October 1998. From November 1998 through April 1999 the machine underwent commissioning half the time and was open half the time for continuing Recycler installation. Since May 1999 the machine has been dedicated to injecting into the Tevatron evey 80 seconds for the last 800 GeV fixed target run. In between Tevatron injections, it has been dumping its entire intensity every 2.5 seconds on a replica of the target for the NuMI beam, in order test target lifetime.

1.1 Main Injector Monument System

The monument system consists of 463 permanent monuments: about an equal number of tierods on the wall and brass plugs in the floor. In addition, there were about 700 temporary "pass" points to help form braced quadrilaterals for determining the coordinates of the permanent monuments. Overlapping measurements of the lengths of legs, angles between points, and elevations were made on these quadrilaterals, using the Chesapeake Laser Tracker, the mekometer, theodolites, and levels. As an example of the redundancy, all lengths were measured three times.

The resulting 22,000 measurements were input to a least squares adjustment program to obtain the best coordinates for the permanent monuments. The propogated error, after scaling to make chisquare/ND equal to one, indicated that the coordinates of each monument had an error in its coordinates of 0.2 mm (1 SD) in all three coordinates, within the region of a betatron wavelength.

Because of the excellence of this monument system, it was decided that it would not be necessary to "smooth" the ring of magnets from magnet to magnet after alignment to the monuments.

Some segments of the monument system had to be readjusted as late as March, 1999, in the vertical plane, for those regions which were covered with dirt late in the construction continued to sink for several months. The section of the MI ring and the Tevatron ring at the tangent point of the two rings actually had to be realigned at the end of the alignment campaign.

This monument systen adjustment has already been well documented at IWAA97 [1] and again in this workshop (see paper by Wojcik and Lakanen).

1.2 Magnet Alignment

The laser tracker was oriented to 3 to 5 monuments in the vicinity of a quadrupole and two dipoles, and these magnets were set to the desired positions. Special software developed at Fernilab allowed us to rotate into the magnet frame-of-reference and align the magnets to within 0.025 mm. The setting tolerance given by the accelerator designers was 0.25 mm; the trim dipoles, one located at each quadrupoles, would easily correct for that (even as an rms) without using more than 30% of their maximum strength on average.

The magnets were aligned to the centerline of their steel laminations, not a magnetically determined axis (for quadrupoles). This choice makes the reasonable assumptions that the laminations were punched with good up/down and left/right symmetry (asymmetry considerably smaller than 0.1 mm, or 0.004 inches) and that the exactness of the coil positions is unimportant (since the steel is only slightly into saturation).

1.3 Error determination

In order to get an approximate quantitative measure of the error with which magnets were aligned with respect to each other, including contributions from the laser tracker setup error and the errors in the monument system, three methods were employed.

In the first approach, we examined 130 quadrupoles which had been set as described above, but were then remeasured days or weeks later, usually with a different one of the laser trackers, but using the same monuments as previously. The rms differences of the previous as-set coordinates and the later as-founds coordinates were 0.11 mm along the beam, 0.15 mm vertically, and 0.15 radially perpendicular to the beam.

In the second approach, 122 quadrupoles were measured twice, once from quite close to the quadrupole just after it was aligned, and then again from 17 m away during the next setup of the laser tracker, with only one monument common to the two measurements. The rms differences were 0.10 mm along the beam and 0.15 mm radially. The fact that these two methods give the same answers shows that the monument system was extremely accurate, at least locally.

Another method is to attempt to deduce the rms misalignment perpendicular to the beam from the rms of the vertical and horizontal correction dipole angles, after they had been tuned to center the beam in the quadrupoles in both planes. The vertical correctors compensate for the quadrupole misalignment and the roll of the dipoles about the beam, and the horizontal correctors compensate for the quadrupole misalignment and the variation from magnet to magnet of the field strength of the dipoles, called by accelerator physicists $(\Delta B/B)_{rms}$. For 85% of the dipoles, $(\Delta B/B)_{rms}$ was 0.04% and contributed negligibly to the demands on the horizontal correctors. Likewise, the rms roll of the dipoles of 0.2 mrads contributed negligibly to the demands on the vertical correctors. The contribution of the quadrupole misalignments to the rms corrector angle is given by the nearly obvious formula,

$$\theta^2_{rms} = (\sigma_Q^2)_{rms} (\beta_{min}+\beta_{max})/(\beta_{max} F^2) \qquad [1]$$

where θ is the correction dipole angle, σ_Q is the quadrupole misalignment, β is the beta function of the lattice, and F is the quadrupole focal length.

From this formula we derive that the quadrupole rms misalignment was 0.43 mm radially and 0.29 mm vertically - much bigger than the results from the first two methods!

Several explanations of this discrepancy are possible, but cannot be proven quantitatively. In either plane, some of the corrector strength may result from quadrupole current coil misplacement making the magnetic center not the same as the center of the steel lamination (see discussion above). The vertical alignment of the quadrupoles may have “decayed” during the year between the alignment and the orbit tuning, a well known effect in all accelerators. We recently discovered a 500 m section of the tunnel which had sunk in the course of a mere six months by 2 mm at the middle of the disturbed region. The orbit may be overcorrected, so that the correctors are running harder than they need be. In the horizontal plane, 15% of the magnets had a $(\Delta B/B)_{rms}$ of 0.2%, 20 times bigger than the rest. Although these magnets were distributed carefully around the ring to minimize their impact on the horizontal correctors, it is clear from the simulations that they put some demands on the correctors.

In view of all these possibilities, the rms misalignments derived from the rms correction dipole angles should be interpreted as an upper limit on the quadrupole misalignments.

3. Recycler Ring

The Recycler Ring is a storage ring of permanent magnets hanging from the ceiling above the Main Injector. Its purpose is to store antiprotons at 8 GeV, injected from the Accumulator Ring when it becomes too full, and also antiprotons “recycled” from the Tevatron at the end of a colliding beams store. The ring has nearly no tunable correction dipoles, so its alignment is even more critical than that of the Main Injector.

This ring was also aligned with the laser trackers, and used the same monument system as the Main Injector. Time did not permit any repeatability studies such as were done in the Main Injector (see above). We believe that the accuracy of the alignment was comparable to that of the

Main Injector. However, we have some evidence that the vertical alignment “decays” faster than in the Main Injector - perhaps a result of the fact that it is hung from the ceiling, which is less stable than the floor.

The long range plan for periodic realignment of the Recycler Ring is not to realign it to monuments, but to move magnets by amounts determined by analysis of the orbit of the particles in the ring (see article by F. Tecker in these proceedings). Further details are also given in a paper by B. Oshinowo in these proceedings.

4. Collider Detectors

The CDF and D0 experiments are in the midst of upgrades with a cost total of about $100 M (not including salaries) and are in constant need of referencing internal components to fiducials which will be accessible during their final alignment to the beamline in the collision hall. Similar jobs are being done for components of the CMS experiment at CERN which are being built at Fermilab. The new V-stars system has been invaluable in these tasks. For more details, see the paper by Oshinowo in these proceedings.

5. Other Recent Activities

The group has also been maintaining the alignment of the Tevatron and the few remaining fixed target experiments. A new collision hall was built which required attention.

5.1 Tevatron maintenance

The Tevatron has not had a systematic realignment since its installation in 1981-1983. Selected quadrupoles have been realigned only when the correction dipoles reached their maximum strength and the cause could be attributed to nearby misaligned quadrupoles. A more systematic realignment will be undertaken during the four-month shutdown of next winter, for a rather large "decay" of the vertical alignment has now been documented.

About 50 quadrupoles have been resurveyed recently, and the other 150 quads were surveyed in 1995. The rms deviation of the elevations from a fitted plane is 1.1 mm, compared to an installation tolerance of 0.4 mm. A few quadrupoles are misaligned by as much as 4 mm. However, locally the ring is smoother: the rms of the difference in elevation of a quadrupole and the average of its nearest neightbors is 0.4 mm.

In addition, the roll angles about the beam of 200 dipoles have been measured, and 41% of them exceed the installation tolerance of 1 mrad. A few are rotated by as much as 8 mrad.

In the horizontal plane only local measurements exist, namely the offset of each quadrupole from the floor plug line to which it was orginally aligned. The rms deviation from the ideal value is 0.4 mm, exactly the same as the local vertical rms deviation.

5.2 Fixed target program

The fixed target program has been reduced to two experiments and one test beam and is now running at 800 GeV for the last time. In a few years, there will be 120 GeV beams to the fixed target area. These experiments and the test beam needed the usual realignment and resurvey.

5.3 C0 collision hall

A small new collision hall at the C0 straight section was constructed during the last year. Its purpose is to house a dedicated B-physics collider experiment around 2005. Construction had to be monitored, the tunnel monument system reestablished, and the Tevatron magnets reinstalled and realigned.

6. Future Activities

The major future projects needing a large alignment effort are two neutrino experiments, MiniBooNE (Booster Neutrino Experiment) and the NuMI (Neutrinos and the Main Injector) project.

MiniBoone uses an 8 GeV beam from the Booster to produce a neutrino beam of less than 1 GeV. The neutrinos are directed to a detector about 500 m away where neutrino oscillations will be searched for in the same domain as the LSND experiment has reported. The alignment here is quite conventional and does not have demands of high precision. The is a conventional charged beam, a horn to focus the pion beam before it decays into muons and neutrinos, and an experiment consisting of just mineral oil and large phototubes.

The NuMI project, which sends neutrinos to a near and far detector of the experiment MINOS (Main Injector Neutrino Oscillation Search) is more challenging. A beam of neutrinos is aimed at the second detector deep underground in a mine 735 km away in Minnesota. The primary proton beam therefore points down at about a 10 degree angle and leads to a target and a 1000 m decay tube which ends about 150 m beneath the earth.

The challenge here is that the experimenters want the beam aimed correctly at the mine to within 3 arc-seconds (15 microradians). Several GPS sessions with receivers on the surface at Fermilab and above the mine have already established the two angles needed and encoded them in the Fermilab above-ground monument network. For further details on the GPS, see the paper by Bocean in these proceedings.

The challenge is to transfer the azimuth to deep underground with the required accuracy. There are two site-risers available from the surface to the final proton beam enclosure with a separation of about 100 m. We plan to transfer the coordinates from above ground through these pipes using two methods: optical plummets and mechanical plumb bobs.

Our initial R&D on a 21 m plumb bob indicates that it agrees with the optical drop to within 0.25 mm (90% CL), and is stable to 0.1 mm when damped in liquid detergent. In addition, we will transfer the azimuth from the surface to the tunnel using the gyrotheodolite, which in recent excercises has proven to be repeatable to 3 arc-seconds, taking forward and backward shots on a baseline. Sometimes it fails to reproduce at the 30 arc-second level, and we continue to work to understand these failures.

7. References

[1] G. Wojcik and S. Lakanen, Proceeedings of IWAA 97, Argonne, IL, USA.