Closed-loop technology speeds up beam control

Brookhaven National Laboratory, Fermilab and CERN have together developed a feedback-control system that is already speeding up operations at RHIC and should prove invaluable in commissioning the LHC. **Peter Cameron** explains.

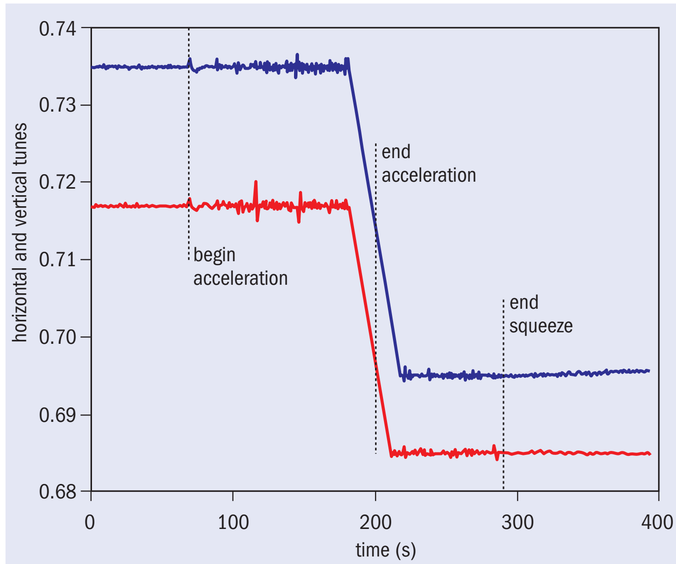

Fig. 1. Data from a typical development ramp early in RHIC Run 6 in February 2006, with tune and coupling feedback enabled. The red and blue traces (left scale) are the betatron tunes.

Successful beam acceleration in the Large Hadron Collider (LHC) at CERN will require accurate and robust control of a variety of machine parameters. With a sufficiently accurate model, it might be possible to control these parameters by the "set it and forget it" method, more often referred to by control specialists as open-loop control. However, in complex systems such as the LHC it becomes advantageous to measure continuously the value of the parameters to be controlled and to adjust the strength of correction elements to maintain the desired values. This method is called closed-loop, or feedback, control.

In addition to correction of absolute position, beam control in the transverse (horizontal and vertical) directions in a synchrotron must regulate two parameters in each plane: betatron tune and chromaticity. The beam in a synchrotron is focused by quadrupole magnets, the equivalent of focusing lenses in optics. The beam particles oscillate transversely in these confining fields, similar to a mass on a spring. This is known as betatron motion and the frequency of oscillation is the betatron tune. In addition, the momentum spread of the beam causes particles with different momenta to experience different focusing, a property of the accelerator known as chromaticity, which is corrected with sextupole magnets.

Equally important is that inevitable magnetic-field errors cause the betatron motions in horizontal and vertical planes to become coupled to each other, and this coupling must be carefully controlled. In the "mass on a spring" model, the horizontal and vertical motions are equivalent to two independent masses vibrating on separate springs, and coupling is a third spring that joins the two masses. This coupling may be corrected with skew quadrupole magnets. Coupling control is often one of the more difficult problems in accelerator control. Inadequate coupling control makes it impossible to control betatron tune properly and also reduces the area of the stable transverse space available to the beam.

Historically, control of tune, chromaticity and coupling has been open loop. However, the LHC pushes design frontiers to the limit, and successful beam acceleration will require closed-loop feedback control of these transverse parameters. In 2002 a collaboration was established between CERN and the Collider–Accelerator Department at the Brookhaven National Laboratory. The purpose was to benefit the LHC from the tune-feedback programme at Brookhaven, and to benefit Brookhaven from CERN expertise. This collaboration is now sponsored by the US LHC Accelerator Research Program (LARP), funded by the US Department of Energy, and has been expanded to include Fermilab. The collaborative effort paid off spectacularly at the beginning of the 2006 run of the Relativistic Heavy Ion Collider (RHIC), with robust control of tune and coupling up the acceleration ramps.

Figure 1 shows data on betatron tunes from a typical development ramp early in RHIC Run 6, with tune and coupling feedback enabled. The drop in tune near the end of the acceleration ramp follows from the fact that RHIC is currently running with polarized protons. The working point used during the acceleration ramp is chosen to minimize growth in the emittance of the beam; once the machine is at full energy the working point is shifted to minimize the effect on the protons of depolarizing resonances. The feedbacks were turned off at the end of the beta squeeze. With the feedbacks on, the largest departures from the desired tunes were around 10^{-3}, while the rms variation of tune was a few 10^{-4}.

The accomplishment of successful ramps with feedback control of tune and coupling was the result of an effort that evolved over ▷

RHIC's tune and coupling feedback could be used at the LHC.

several years. Early efforts at RHIC were persistently confounded by two obstacles. The first was a problem of dynamic range. To avoid blowing up the transverse size of the beam, and thereby reducing the beam brightness available to the physics experiments, the beam excitations needed to measure and control tune must be very small. The power in the resulting betatron signal is of the order of femtowatts (10^{-15} W), while the power delivered to the pickup by the beam unrelated to the betatron tune is in the range of tens of watts. We therefore devoted our attention to this dynamic-range problem, attempting many solutions, all with only partial success. Ultimately, CERN provided the solution by way of an analogue front-end using direct diode detection, or "3D" (Gasior and Jones 2005).

The second obstacle to tune feedback at RHIC was linear coupling, which rotates the planes of the betatron oscillations away from the horizontal and vertical in which the magnet portion of a tune-feedback loop applies corrections. When this rotation approaches 45° the magnet loop then applies tune corrections in the wrong plane relative to the tune measurement, and the tune-feedback loop is driven unstable. RHIC (like the LHC) requires strong sextupoles to compensate for natural chromaticity; unfortunately, vertical offset in the sextupoles introduces coupling, and vertical-orbit fluctuations from ramp to ramp in RHIC were often sufficient to cause the tunes to become fully coupled.

In 2004 we fully understood the coupling problem, so efforts to implement tune feedback ceased, and we began to implement coupling feedback. We reconfigured the tune-measurement system to measure both projections of the tunes in both planes during tune tracking. Due to hardware limitations, this could be done in only one ring at a time. However, the excellent quality of the resulting data made it clear that we could implement coupling feedback. Over the course of the next two years this was studied in some detail and a decoupling algorithm was formulated (Cameron *et al.* 2005 and Luo *et al.* 2005).

For the 2006 run at RHIC a new system for measuring baseband tune – or baseband Q (BBQ) – was developed. This incorporates measurement of both tunes in both planes in both rings, as well as the 3D analogue front ends. The system was extensively commissioned on analogue test resonators before working with a real beam, both for tune and coupling measurement. Within minutes of the first circulating bunched beam in RHIC, the BBQ was measuring tune and coupling "out of the box". During the period of machine set-up and tuning in preparation for developing acceleration ramps, the control-system interface to the magnets was completed, together with measurements of overall system loop gains and the design of the loop filters.

Ramping began on the evening of 15 February. The beam was lost early in the first ramp, which was done without tune and coupling feedback to establish a baseline. For the second ramp the feedback loops were closed and the beam was delivered to full energy, with tune control of around 0.001 or better, with the machine well decoupled throughout the ramp. This successful ramp was the world's first attempt to implement simultaneous tune and coupling feedback during beam acceleration – good news for the LHC. There is now a reasonable expectation, given sufficient attention to integration with the controls and magnet systems, that an operational tune- and coupling-feedback system will be available early in the LHC commissioning.

As the tune- and coupling-feedback system for RHIC moves towards full operational integration as a "non-expert" system, the focus for instrumentation has shifted to chromaticity control and feedback. As valuable as robust tune and coupling feedback will be for LHC commissioning, the most urgent need will be for chromaticity measurement and control, to combat the chromatic effect of "snapback" transients at the beginning of the acceleration ramp.

Many approaches to the problem of fast and accurate chromaticity measurement during ramping are being investigated. The most promising approach implemented so far tracks tune while simultaneously modulating the beam momentum very slightly. Measurement of the resulting tune modulations has permitted determination of chromaticity during ramping with an accuracy of around a unit, and a bandwidth of about 1 Hz. This method has been operational in RHIC for the past two years as a non-expert measurement under sequencer control (Cameron *et al.* 2005). During the coming weeks and months both this and other methods will be further evaluated at RHIC, in close collaboration with Fermilab and CERN, and we look forward to reporting here on successful results from these efforts.

- For more about US-LARP see www.agsrhichome.bnl.gov/LARP/.

Further reading

P Cameron *et al.* 2005 "Advances Towards the Measurement and Control of LHC Tune and Chromaticity", DIPAC 2005, Lyon.
M Gasior and R Jones 2005 "High Sensitivity Tune Measurement by Direct Diode Detection", DIPAC 2005, Lyon.
Y Luo *et al.* 2005 "Possible Phase Loop for the Global Decoupling", PAC 2005, Knoxville.

Résumé

Contrôle de faisceaux amélioré

Pour accélérer des faisceaux dans le Grand collisionneur de hadrons (LHC) du CERN, il faudra disposer de systèmes de contrôle-commande précis et fiables pour différents paramètres – en particulier, la fréquence de l'oscillation bêtatron ("l'accord bêtatron") et le couplage des oscillations sur différents plans. Une collaboration entre Brookhaven, Fermilab, et le CERN a mis au point un système de contrôle avec rétroaction, dans le cadre du programme américain LARP de recherche sur les accélérateurs. Il s'agit du premier système au monde assurant simultanément une rétroaction sur l'accord et sur le couplage pendant l'accélération du faisceau. Ce système permet déjà un réglage plus rapide du Collisionneur d'ions lourds relativistes (RHIC). Il devrait être extrêmement précieux lors de la mise en service du LHC.

Peter Cameron, *Brookhaven National Laboratory.*