IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June 1981

THE ISABELLE ACCELERATOR SOFTWARE, CONTROL SYSTEM, AND BEAM DIAGNOSTIC PHILOSOPHY*

M. Cornacchia, J.W. Humphrey, J. Niederer, and J.H. Poole

Brookhaven National Laboratory
Upton, New York 11973

Summary

The ISABELLE Project combines two large proton accelerators with two storage rings in the same facility using superconducting magnet technology. This combination leads to severe constraints on beam loss in magnets and involves complex treatment of magnetic field imperfections and correction elements. The consequent demands placed upon beam diagnostics, accelerator model programs, and the computer oriented control system are discussed in terms of an illustrative operation scenario.

Introduction

ISABELLE is unique among major proton accelerators in that its main rings must serve both as accelerators and as storage rings. Furthermore, significant beam loss into the superconducting magnets is intolerable. The time to set up a stack and accelerate it is likely to be long, perhaps a matter of many hours. Hence streamlining of beam set up procedures will be essential. It will not be practical to make repeated attempts to launch and measure one full acceleration cycle, and then adjust on the next one as in conventional fast cycling machines. These features appear to lead to very harsh requirements in the organization and operation of ISABELLE and its control procedures. The technology which is expected to support these procedures includes an emphasis on fast reliable beam diagnostics, interpretive and modelling software, and general data management and transport components.

Magnet Properties and ISABELLE Operations

Multistage injection and stacking procedures will be invoked to supply each physics run with coasting, colliding beams. These procedures are complicated by the sensitivity of magnets to radiation. The relevant constraint is that a beam loss of 10^9 protons into a given magnet may cause a quench. This limit is only a small part of the intended full current of 6.4×10^{14} circulating protons (8 amps). The chance of losing beam into magnets is necessarily greatest at injection energies, when the beam must fill the usable part of the physical aperture to achieve maximum luminosity. Thus the edges of the beam are very close to the vacuum chamber walls. On the other hand, the magnets are more radiation tolerant at low fields. Their sensitivity to beam loss grows rapidly with increasing field and beam energy, perhaps balancing a corresponding decrease in beam spot size. Because of these competing factors it is clear that extreme care against beam loss must be exercised throughout the entire energy range.

Adding further to these difficulties, field non-linearities, which are more pronounced because superconducting coils are much closer to the walls than in conventional magnets, play a significant part in determining orbit stability and behavior. Correction windings with fields up to duodecapole are employed to control these aberrations and shape the working line. Rate dependent effects during magnet ramping, magnetization effects, and saturation effects will further complicate the correction picture. Drifts such as the variation of magnetization with temperature will also be of some importance, especially when the momentum spread is still large. Extensive measurements to be carried out on magnets following assembly will allow a systematic treatment of many of these effects for later use in model programs within the control system.

Every effort will be made to make the ISABELLE magnet and the acceleration systems extremely stable and predictable. We nevertheless will offer a substantial amount of forgiveness within the more global operations and control structures. This can be carried out by rearranging somewhat the way in which conventional control logic elements are used. In particular, the acceleration procedures will be built to handle a worst case scenario in which a number of accelerate, check, and correct moves are executed in turn. The parameters for each move, established from primary design and commissioning experience, are to be adjusted more finely in setup routines with test beams at the start of a major cycle, and finally are to be altered on the fly by responding to the checks which would accompany each acceleration move. The spacing and duration of the moves will reflect accumulating confidence and experience, and also the level of stability of the machine as a whole. In the ideal, this strategy should also be able to handle a spectrum of likely acceleration cycles from a single ramp to multi-ramp with intermediate flat tops, and from totally operator sequenced to fully automatic.

Trimming the Lattice with Test Cycles

One practical way to help avoid quenching magnets is to initiate and check accelerator systems with low intensity test beams. Here we sketch likely steps by which central control sequences might be verified with a test beam, and relate these steps to necessary orbit measurements and lattice adjustment procedures. These trial runs must be carried out in times short compared with system drifts or other changes if they are to be useful as guides for the full cycle to follow. The fact that they are also an overhead is further incentive for rushing. In this discussion we are more concerned with showing the type and the power of a

*Work performed under the auspices of the U. S. Department of Energy.

0018-9499/81/0600-2264$00.75©1981 IEEE

newer generation of general purpose accelerator operations tools than the precise details of future beam preparation cycles.

In a representative sequence, the injection orbit would be observed with a low intensity test beam of on momentum protons and corrected as necessary. We avoid the details of passing protons over the transfer line from the AGS which prepares them for injection at 30 Gev. This step would be followed by measurements of the orbits and tunes for a grid of momenta, typically in the range of $\Delta P/P \sim \pm$ 1%, again using low intensity beams. Corrections to orbit, tune, and chromaticity would be derived from these data, applied, and results checked with subsequent injection pulses. Other parts of the injection system would then be further optimized, for example the setting of the RF feedback system for damping coherent injection oscillations.

A series of measurements of the central orbit and tune will be made on a small test beam during a trial acceleration cycle. We will endeavor to measure the beam without perturbing it, so a single test injection can be used over a full energy range. This test beam will remain bunched. A series of tune measurements, stepped through the acceleration cycle, will be made with a bunched beam Schottky scan system. The central orbit and tune will be adjusted from each group of measurements, using dipole and quadrupole correctors, within each step. A large number of controllable parameters, 254 in the magnet system alone, may be fine tuned during this and succeeding phases of the lattice test and full acceleration cycle.

The next stage repeats the trial acceleration process for slightly off momentum bunches near the extremes of the acceptance, ie $\Delta P/P \sim \pm$ 1% . At energies up to about 100 Gev the aperture restrictions will be severe, so it will be prudent to carry these test beams near the edge of the momentum acceptance to at least this energy. Measurements recorded while accelerating off-momentum bunches will be used to further trim the multipole correctors. Most of this test and calibration data would be available as an empirical guide for real time adjustments during the full beam cycles which follow.

The vertical orbit and dispersion at the intersections would be measured next at the collision energy and corrected further using the correction dipoles, still using small test beams, working in one ring at a time.

The Full Beam Cycle

In this example scenario, the full beam cycle involves injection, stacking, acceleration and coasting beam phases. Stacking is a combination of synchronization and RF gymnastics to build up beam with bunches of protons from the AGS injected into the rings of ISABELLE. It must be accomplished with minimum loss and dilution of beam. As the stacked beam intensity increases, multipoles distributed in the main lattice magnets will be used to compensate for space charge. The stack must be regarded as a precious quantity because it will probably take several hours to obtain. At this stage the non-perturbing and accurate diagnostics become essential. Once again Schottky systems will be used to monitor the stack, and any further corrections to the working line will be applied by means of multipole correctors. The possibility of field drifts during the lengthy procedures must be anticipated, and are to be accommodated by real time control mechanisms where feasible.

During the acceleration phase which follows stacking, the working line and orbit must be closely controlled. All magnets and the RF system must track together. Numerous variable control elements must be coordinated to compensate for additional anticipated non-linear effects in the lattice. Besides multipolar field errors which depend on both ramp rate and location in ramp cycle, decreasing beam size, varying space charge forces and similar time dependent contaminants may affect the settings obtained with test beams. Because of the delicate nature of the stack, corrections will have to be made smoothly, and with proper respect for the intricate interrelationship of the several non-linearities. The procedures mentioned must be carried out for both beams from injection through full acceleration.

Once at full energy, the beams enter a coasting state, where they are further analyzed and then prepared for collision and physics activities. The stability and lifetime of the beams are optimized through continuous minor adjustments to the working line and stability diagram derived from beam measurements. For physics purposes, both luminosity and radiation backgrounds may require further tuning of the orbit in the vicinity of the interaction regions with appropriate correction dipoles. Beam-beam interaction effects will probably also enter into this complex series of monitoring and adjustments.

Beam Diagnostics

The character of ISABELLE beams themselves will be an important monitor of the performance of the complex magnet lattices of the rings. We plan to record conventional closed orbit information, that is vertical and horizontal beam centers, at over 100 locations in each ring, spaced at intervals of about one quarter betatron wave length. Each will be sensed by pickup electrodes with an effective sampling time of about .15ms. We believe that such information can now be exploited rapidly enough to be used realistically in lattice control and feedback procedures. Total processing times should not prolong the fastest expected acceleration time of eight minutes. The fragility of beams and magnets offers a major incentive to use closed orbit analysis in a real time sense.

We intend to use Schottky scan systems to record frequency spectra which are processed to deliver momentum profiles, tunes, tune spreads, working lines, wall and feedback impedences, and stability margins. Such systems will be used on both bunched and on coasting beams.[1] A combination of low synchrotron frequency, (~ 1Hz), long stored bunches, and high intensity favor our use of a bunched beam scanner. These devices require significant computer power to resolve the data in the spectrum. We will try to equip these to match general goals of several second or less response times for possible use in beam control feedback assignments.

Creative Control Computing

The combination of injection and acceleration, a low threshold for beam loss mischief and long preparation periods suggest that ISABELLE must surpass considerably the already admirable control features achieved in other machines. Accordingly modelling and orbit trace services are to be routinely provided based upon sensors and modern computing equipment and techniques. We view the problem of providing continuous control reliability as paramount, and will call upon fault tolerant methods to insure the necessary level of performance. Rapid sensing of orbits at multiple sites and immediate digestion of such measurements are required. Local fault tolerant data stations to be built of micro computer nets will continuously accept and collate orbit data, and submit it to central modelling based programs as requested. A number of these stations must operate in parallel to provide realistic speed and timing for the entire acceleration interval. The major functional parts of ISABELLE that will provide these measurement, analysis and control services consist of outlying distributed stations linked to a central console and computer group by a common cable.

Current accelerator modelling programs are large and tax big computers. Ray trace computations which include multipole effects consume minutes of 7600 time for routine runs through the ISABELLE lattice. These are well beyond the reach of conventional minis, and larger scale general purpose computers are overly expensive to be considered as integral parts of the control system. Fortunately it is now possible to assign a heavy computational element to one kind of module and more conventional message and transaction processing elements to another. Both array processors and physics emulators or computing engines have achieved the proper scale of power for building accelerator modelling into the control system, are well suited to such dedicated tasks, and are reasonable in cost. Moreover these specialized floating point engines can be given nearly all heavy central computing assignments. More conventional mini computers can be selected to be essentially control network transaction processors, which also serve the needs of the attached engines. Given this separation of function, the mini roles can be duplicated or backed up. These tandem techniques specifically deliver fault tolerant, unfailing management of operations to the console. A guide to this methodology can be found in Bartlett[2] and Katzman[3]. There are commercial offerings adequate for both transaction handling and computing engine duties.

Although these hardware advances will help to bring tools such as closed orbit programs into the everyday world of accelerator control, faster response times will come from basic revisions of the programs themselves. Most involve matrix representation of lattice properties. Running speeds can be reduced with more compact algorithms, and by applying conventional optimizing tricks to the code, keeping in mind the specific magnitudes and ranges of the various lattice quantities. Lattice elements can be grouped, expressed more efficiently, combined analytically, and often expanded as appropriate to the control or correction variables involved. Such reorganization of the computations can be made much faster than a less disciplined matrix multiplication found in usual approaches. Some of the task of maintaining and updating the matrix elements derived from measured quantities can be assigned to outlying micros which gather the raw magnet data. A number of such micros working in parallel spare the central engines from treating raw data in serial fashion in setting up the matrices. These and similar possibilities are being studied in detail. We believe that running times of the order of seconds are necessary for this closed orbit feedback approach to be practical.

Beam sensing and sampling procedures, and subsequent organization and submission of data to the modelling programs are intended to be transparent to accelerator operators. This acquisition and managing of what is effectively a part of the accelerator data base is expected to be responsive, with minimal time delays during the various ordered moves by which magnets are ramped, beams are accelerated, and results monitored. These conditions in turn determine the needed bandwidth of the communications that link the central system to the sensors and their collecting stations. Likewise, they dictate that local stations be fast and intelligent, and have adequate memory to handle their individual parts of the collective data base. We expect to achieve an order of magnitude better response by distributing this role to the local stations instead of treating beam data serially in a central data reservoir. The central computing engines will absorb data blocks via a communications cable from attached stations much like they were logically sections of a direct access disc device. In view of the wide range of potential difficulties presented by extreme tolerance requirements on magnets, and the various multipole presences and effects, the data collection and organization process must be at least as fast as the central modelling and other programs which depend on data to track and correct beam acceleration progress. Extended system response time is to be avoided, as it must be regarded as friendly to developing instabilities. Stations are expected to have beam position read and record times of under a millisecond. Approximately 110 xy position sensors per ring will be distributed among 24 stations. A communications overhead delay of under a millisecond is planned. Thus we seek to provide a beam position data base which is current within a tenth second and preferably much less. Cataloguing of trend data will offer additional compensation for this remaining latency.

The stations have a very critical role, and must be dependable throughout the life of a storage cycle. It seems feasible to assemble them as small clusters of closely linked micros, in which the cluster as a whole functions as a fault tolerant computing element. Relevant prototype system software for such nets is emerging commercially. A predecessor of such a product is described in Wensley.[4].

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