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COMPUTATION APPLIED TO PARTICLE ACCELERATOR SIMULATIONS*

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ABSTRACT

The rapid growth in the power of large-scale computers has had a revolutionary effect on the study of charged-particle accelerators that is similar to the impact of smaller computers on everyday life. Before an accelerator is built, it is now the absolute rule to simulate every component and subsystem by computer to establish modes of operation and tolerances. We will bypass the important and fruitful areas of control and operation and consider only application to design and diagnostic interpretation. Applications of computers can be divided into separate categories including:

- component design,
- system design,
- stability studies,
- cost optimization, and
- operating condition simulation.

For the purposes of this report, we will choose a few examples taken from the above categories to illustrate the methods and we will discuss the significance of the work to the project, and also briefly discuss the accelerator project itself. The examples that will be discussed are:

(1) the tracking analysis done for the main ring of the Superconducting Supercollider, which contributed to the analysis which ultimately resulted in changing the dipole coil diameter to 5 cm from the earlier design for a 4-cm coil-diameter dipole magnet;
(2) the design of accelerator structures for electron-positron linear colliders and circular colliding beam systems (B-factories);
(3) simulation of the wake fields from multibunch electron beams for linear colliders; and
(4) particle-in-cell simulation of space-charge dominated beams for an experimental linear induction accelerator for Heavy Ion Fusion.

SSC APERTURE STUDY

One of the important issues for the SSC was the size of the superconducting dipole magnets to be used.[1] More protons can survive in the collider rings with dipoles of larger coil diameter because larger coil-diameter dipole magnets can provide more uniform bending magnetic field. However, larger dipole magnets are more expensive. Therefore, one must study the proton motion for each of the alternative magnet lattices under consideration. This was done by simulating the motion of the proton beam with numerical codes on supercomputers.

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In these numerical studies, one starts with a well-designed linear lattice and then assigns systematic errors, random errors, and misalignment for the magnets, based on experience and measurement. Correction magnets may also be included. Ideally, protons are then tracked numerically for a limited number of turns to see if the motion is stable. At this stage, adjustment of the correction magnets is usually necessary (somewhat similar to the micro-tuning of a TV or a radio). After the accelerator is well tuned, one can start short-term tracking (say, 400 turns) to study some well-defined accelerator physics criteria to predict the behavior of the accelerator.

Fig. 1. Phase space plot p_x versus x for four protons with different initial amplitudes, where x is a Floquet space coordinate and p_x is its corresponding Floquet space momentum; that is, they are normalized such that a proton with linear motion would trace out a circle. The variation in the amplitude traced out by a given proton serves as a diagnostic of accelerator nonlinearity of that proton's motion. For example, the protons here with the smallest initial amplitude show so little nonlinearity that the data points merge into a solid line. However, the protons with the largest initial amplitude have correspondingly greater nonlinearity, so that the data points are more widely spaced in the circular band.

A typical short-term-tracking phase space plot is shown in Fig. 1. The variation in the amplitude traced out by given protons is greater for those protons of larger initial amplitude. Here, as shown in Fig. 1, the amplitude is defined as $\sqrt{x^2 + p_x^2}$, where x is a Floquet space coordinate and p_x is its corresponding Floquet space momentum; that is, they are normalized such that a proton with linear motion would trace out a circle in (x, p_x) phase space. This phenomenon serves as a diagnostic of accelerator nonlinearity. If the amplitude variation is considered too big for a certain desired amplitude, the corresponding accelerator design should be modified.

Generally, one would be more concerned with the long-term stability of the protons. One would like to track hundreds of protons (with appropriate initial amplitude distributions) around the ring element-by-element for 100,000 turns or more (0.5 minutes of SSC operation will be about 100,000 turns). Using a current scalar computer, this would require months of central processing unit (CPU) time, since there are more than 10,000 magnet elements in the SSC machine. Fortunately however, the protons in the beam may be considered to be independent from each other, so that a tracking code can be completely vectorized over the number of particles; thus, a supercomputer is ideal for this purpose. One can track many particles (say, 64 protons) simultaneously, saving enormous CPU time over what a scalar machine would require.

Figure 2 compares the tracking data up to 100,000 turns for a collider injection lattice (at 2 TeV energy) using 4-cm coil-diameter dipole magnets, with the corresponding data for the same lattice using 5-cm coil-diameter dipole magnets. None of the particles with initial displacement amplitude of less than 8.1 mm were lost in the 5-cm coil-diameter dipole magnet case; but in the 4-cm coil-diameter dipole magnet case, particles still get lost until their initial displacement amplitude is reduced to about 5.3 mm. The only difference between the two lattices was in the multipole content, due to the different size of the magnet aperture. With the increase in magnet aperture from 4-cm coil-diameter to 5-cm coil-diameter, the stable region of the proton motion for 100,000 turns enlarged from about 5.3 mm to about 8.1 mm in radius. Based on these numerical studies and many other investigations, the 5-cm coil-diameter superconducting dipole magnets have been chosen.

Fig. 2. A hundred-thousand-turn survival plot for a collider 2-TeV injection lattice, comparing the data for a 5-cm magnet aperture with the data for a 4-cm magnet aperture. With the 5-cm aperture, no particles with initial displacement amplitude of less than 8.1 mm were lost. By increasing the magnet aperture, the dynamic aperture for 100,000 turns enlarges from about 5.3 mm to about 8.1 mm in radius, which increases the machine's linearity. (This plot shows only the protons that were lost before 100,000 turns are reached.)

DESIGN OF ACCELERATOR STRUCTURES

The purpose that the accelerator structure serves is to provide a means for converting the electromagnetic power into fields that can efficiently and accurately couple power into the charged particle beams. Thus the structure must have an entrance, or port, through which electromagnetic energy can flow, and cooled walls to remove the heat generated by surface currents in the structure walls. Typically the structure must be designed to be resonant at the frequency that is chosen for the accelerating mode. It is often just as important that the structure not be resonant at frequencies that correspond to modes that can improperly steer the particles. From just the above conditions we have several requirements on the structure:

(1) dimensionally accurate to resonate at frequencies ranging from a few hundred megahertz to several million megahertz,

(2) dimensionally stable and properly cooled to maintain the dimensions needed to stay tuned to the drive frequency, and to keep away from damaging resonances, and

(3) non-cylindrical symmetry to allow for a port to permit the flow of electro magnetic power.

Structures can be either made of normal conductors, usually copper, or of superconducting materials, usually niobium alloys. Superconducting cavities are especially useful for continuous operation for installations such as the Continuous Electron Beam Accelerator Facility. For pulsed operation, with very high electric fields and high beam currents, normal conducting copper cavities are appropriate. In either case, it is important to consider fields left by the particles themselves, as they can affect particles coming through the structure later.

Figure 3 is a view of the parts of a test cavity[1] for a future electron-positron linear collider. To achieve very high electric fields, which are important if the accelerators are to be kept to a reasonable length, it is necessary to go to very high frequency RF power. The device in Fig. 1 is designed for 11.42 gigahertz, which corresponds to a wavelength of 2.62 cm, about one inch. This frequency corresponds to the range that is designated as X-band.

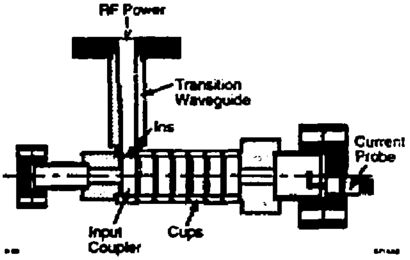

Fig. 3. Test structure for an X-band accelerator.

Figure 4 shows the three dimensional (3-D) mesh zoned for the structure shown in Fig. 1. In order to conserve on computation time and memory, only one half of the structure is modeled. With 500,000 zones, as shown in Fig. 3, 2 to 3 hours of Cray 2 time are needed to model the structure and find the necessary number of higher-order modes. A memory space of 10 million words is needed to make the simulation of the fields. Although higher resolution would be very useful, another factor of two increase in the number of mesh points is not currently possible with present facilities.

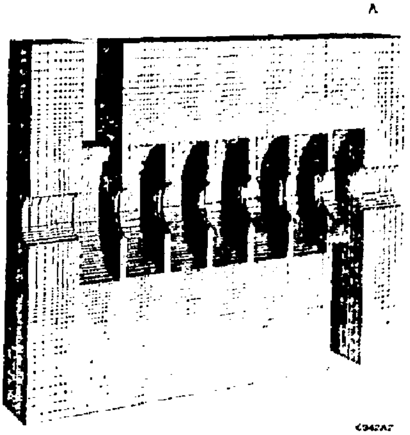

Fig. 4. Three-dimensional zoned model of the X-band structure shown in Fig. 1. About 500,000 zones are needed.

Figure 5 shows an accelerating structure[2] for the asymmetric storage rings operating at the production resonance for B particles, thus earning the designation B-factory. Although not at the highest center-of-mass energy, B-factory design is especially demanding because of the very high circulating electron currents that are required. Because the RF fields are provided continuously, the high average power needed to maintain the collision rate requires exceptional care in designing for heat dissipation and cavity cooling. The results of the design study with this simulation were used to provide input to a cavity heat-load study.

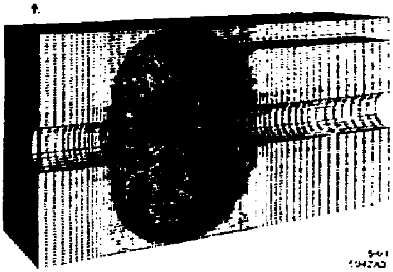

Fig. 5. The 3-D zone for the B-factory RF structure includes reentrant nose cones and an input coupler.

WAKE FIELD SIMULATION

The residual fields, or "wake" fields as they are named by analogy to the wake of a boat, can disrupt particles in bunches that follow in the wake of leading bunches. This problem can be controlled if the accelerating structures can be designed so that the damaging modes are sufficiently loaded, for instance by providing an escape path for the fields, or if the structures are designed so that a wide variety of resonant frequencies are present for higher modes.

The wake fields from a moving bunch of charged particles can be calculated using the programs BCI and TBCI (transverse beam-cavity interaction) by T. Weiland[3] These programs are similar to the large particle-in-cell programs such as ARGUS (in 3-D) Condor in (2-D) and are related to the more recent work by Weiland for the Mafia code group. Figure 6 shows the transient wake fields of a bunch of charged particles passing through a cavity, as calculated by Bane, Chao and Weiland.[4]

Fig. 6. The transient electromagnetic fields in a cavity as a bunch of electrons (shown in the position of the Gaussian curve below the axis) passes through the tube. The cavity in each view is the same cavity at a later instant.

A somewhat different problem is presented for the wakes within a single bunch of particles, by which particles off the axis cause fields which can displace particles within the same bunch. Single bunch effects were simulated by Bane.[5] The effect of these fields can be seen in the computer simulation shown in the left side of Fig. 7. Based on suggestions by Balakin et al.[6] Bane calculated the effects of introducing a small, controlled energy spread into the bunch. The effect known both as Landau Damping, and as BNS damping for the Soviet scientists who suggested this solution, is that the bunch remains well aligned as shown on the right side of Fig. 7. The energy differences remain correlated with position in the bunch so that manipulations of the phase of the RF power at the end of the accelerator can cancel the spread in energy.

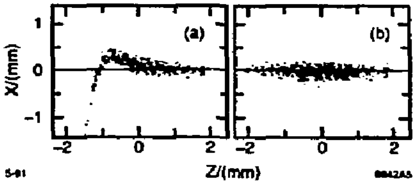

Fig. 7. Bunch shape without Landau Damping (on the left) and with the damping effect (on the right).

COMPRESSION OF HEAVY ION BEAMS FOR FUSION

Intense beams of heavy ions can be used to implode and ignite targets of deuterium and tritium to make Inertial Fusion Energy (IFE). Studies of focusing, bending, and especially the longitudinal compression necessary to increase the peak current in a bunch, are made with a new 3-D simulation program called WARP.[7]

In Fig. 8, a bunch of heavy ions is shown before beginning final compression and then again after undergoing some compression. Compression is accomplished by imposing a longitudinal velocity tilt on the ion beam, by accelerating the trailing (left) end of the bunch more than the leading end. After two-thirds of the compression process, the bunch profiles are as shown in the lower two figures. The shapes are controlled at any one point by the quadrupole focusing system which alternately focuses and defocuses the beam in the two orthogonal planes. Thus at any one point along the beam, the beam profile will be elliptical in shape. The primary concern in beam manipulations of this type is the degree to which the beam quality, or emittance, is disturbed by the compression.

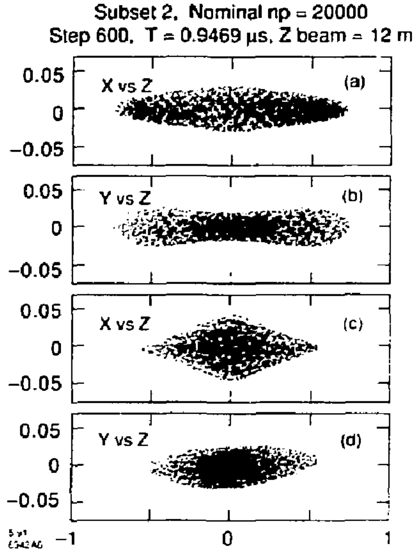

Fig. 8. Longitudinal compression is studied using the 3-D program WARP. The longitudinal spatial distribution is shown for both the X-Z and Y-Z projections in the upper pair of figures. The compressed bunch is shown in the two lower figures.

Thus it is necessary to use a great many particles (20,000 macro particles were used in this example) and very small time steps in order to maintain the accuracy of the calculation.

As the compression continues, the longitudinal line-charge density increases as shown in Fig. 9. Early experiments at LBL with the MBE-4 experiment have demonstrated longitudinal compression of this type. The simulations shown here are of the conditions as the beam is focused towards the target in the reactor vessel, and are thus far beyond what is available experimentally.

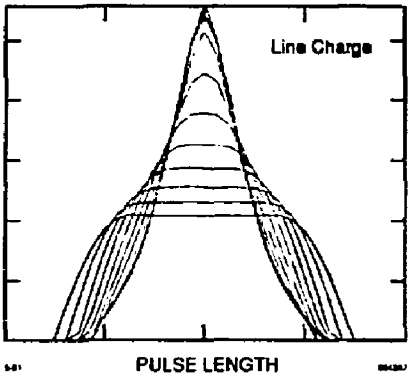

Fig. 9. Line-charge density of the compressed bunch shown at several different times during the compression process.

CONCLUSIONS

Computers play an ever-expanding role in the study of particle accelerators. Accelerators are growing in importance to research and industry, and may one day be an important part of the energy production industry. The economic arguments clearly favor the purchase of larger, faster computers which are far less expensive than the machines that they help design. In some areas, especially those involving 3-D modelling of RF cavities and intense beams, the applications are limited by the size and speed of the computers.

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