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Applications of Large-Scale Computation to Particle Accelerators*

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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 from the above categories to illustrate the methods used, and discuss the significance of the work to the project. We also briefly discuss the accelerator project itself. The examples that will be discussed are:

- The design of accelerator structures for electron-positron linear colliders and circular colliding beam systems (B-factories).
- Simulation of the wake fields from multibunch electron beams for linear colliders.
- Particle-in-cell simulation of space-charge dominated beams for an experimental linear induction accelerator for Heavy Ion Fusion.

In a separate paper at this meeting, Dr. Yitan Yan is presenting simulations of the orbit stability of the Superconducting Super Collider (SSC). A more complete discussion of the computer design of accelerator structures is the subject of a poster presentation by Dr. Kwok Ko.

Invited talk presented at the Power Supercomputer Users Meeting, Gaithersburg, Maryland, May 21–22, 1991.

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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:

- dimensionally accurate—to resonate at frequencies ranging from a few hundred megahertz to several million megahertz,
- 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
- non-cylindrical symmetry—to allow for a port to permit the flow of electromagnetic 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 1 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.

Figure 2 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. 1, two to three hours of Cray-2 time are needed to model the RF filling of the structure to study transient effects. 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.

Figure 3 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

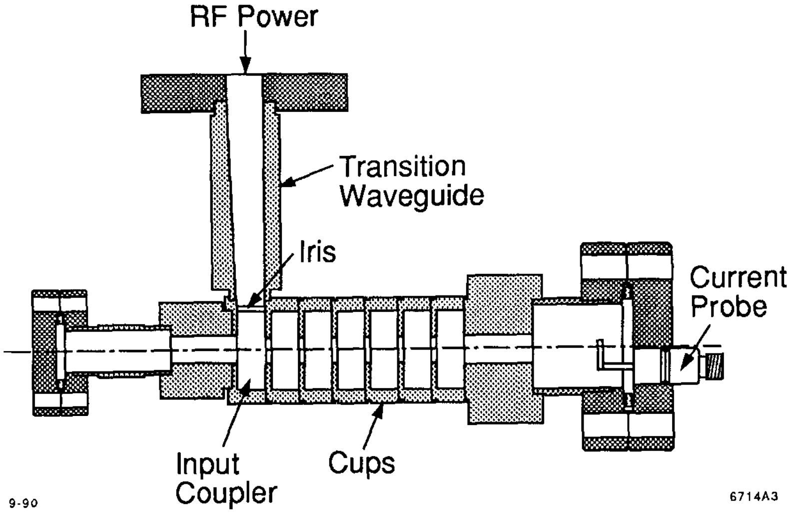

Fig. 1. Test structure for an X-band accelerator.

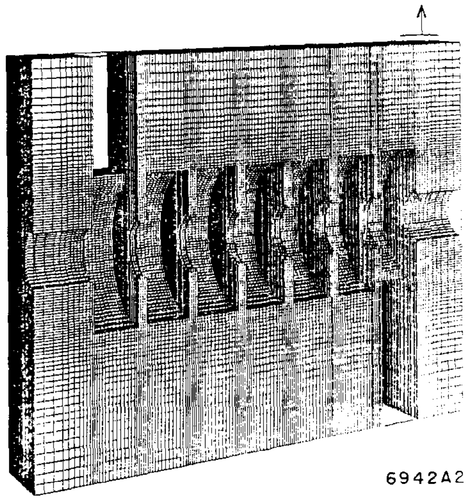

Fig. 2. Three-dimensional zoned model of the X-band structure shown in Fig. 1. About 500,000 zones are needed.

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.

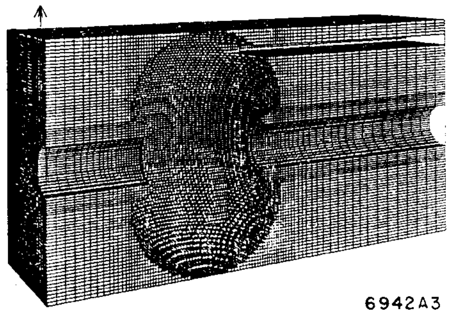

Fig. 3. The 3-D zone for the B-factory RF structure includes reentrant nose cones and an input coupler. A memory space of 10 million words is needed to make the simulation of the fields.

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)or Condor in (2-D), and are related to the more recent work by Weiland for the MAFIA code group. Figure 4 shows the transient wake fields of a bunch of charged particles passing through a cavity, as calculated by Bane, Chao, and Weiland [4].

A somewhat different problem is presented for the wakes within a single bunch of particles, where 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 on the left side of Fig. 5. Based on suggestions by Balakin et al. [6], Bane calculated the effects of introducing a small, controlled energy spread into the bunch. This effect—known both as Landau Damping and as BNS damping, for the Soviet scientists who suggested this solution—dissipates the wake fields and allows the bunch to remain well-aligned, as shown on the right side of Fig. 5. 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.

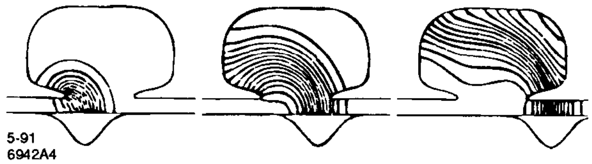

Fig. 4. The transient electromagnetic fields in a cavity as a bunch of electrons (shown in the position of the Gaussian curve below the axis) passes through the tube. The cavity in each view is the same cavity at a later instant.

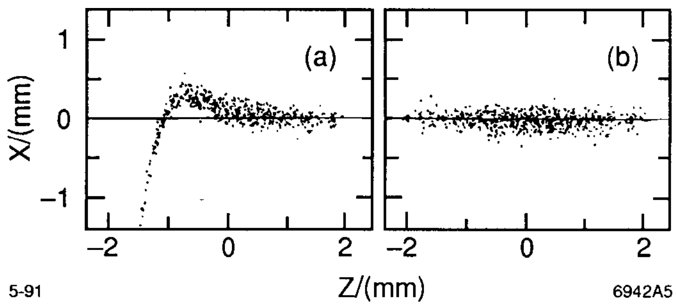

Fig. 5. Bunch shape without Landau Damping (on the left) and with the damping effect (on the right).

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. 6, 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 that alternately focuses and defocuses the beam in the two orthogonal planes. As a result, 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. Therefore, 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.

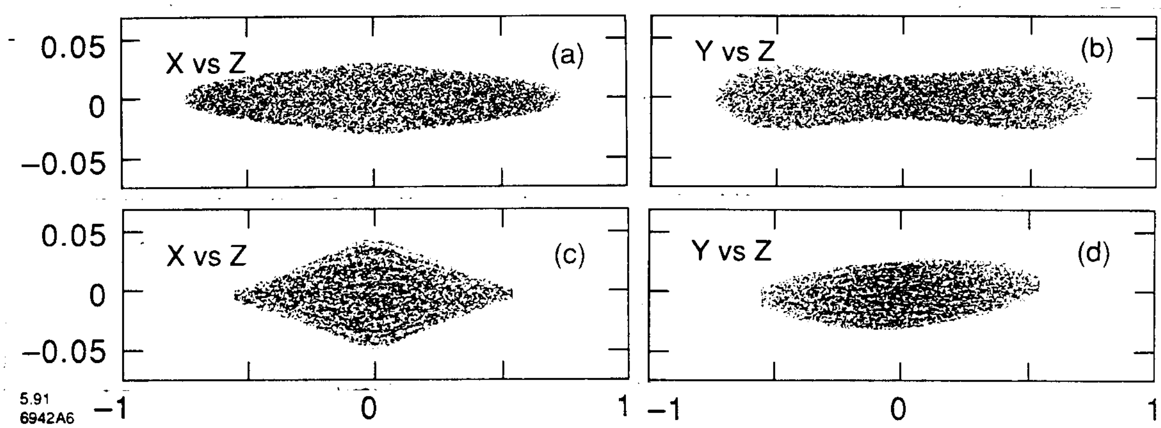

Fig. 6. Longitudinal compression is studied using the 3-D program WARP. The longitudinal spatial distribution is shown for both the X-Z and Y-Z projections in the upper pair of figures. The compressed bunch is shown in the two lower figures.

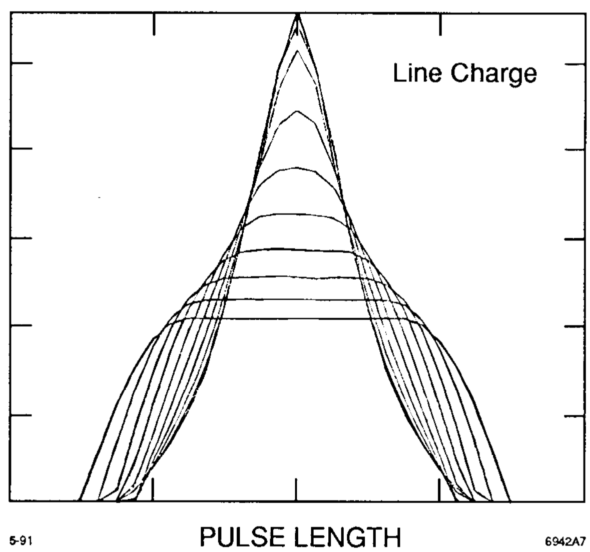

Fig. 7. Line-charge density of the compressed bunch shown at several different times during the compression process.

As the compression continues, the longitudinal line-charge density increases as shown in Fig. 7. Early experiments at LBL with the MBE-4 experiment have demonstrated longitudinal compression of this type. The simulations shown here are for conditions as the beam is focused towards the target in the reactor vessel, which are far beyond what is available experimentally.

Conclusions

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

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