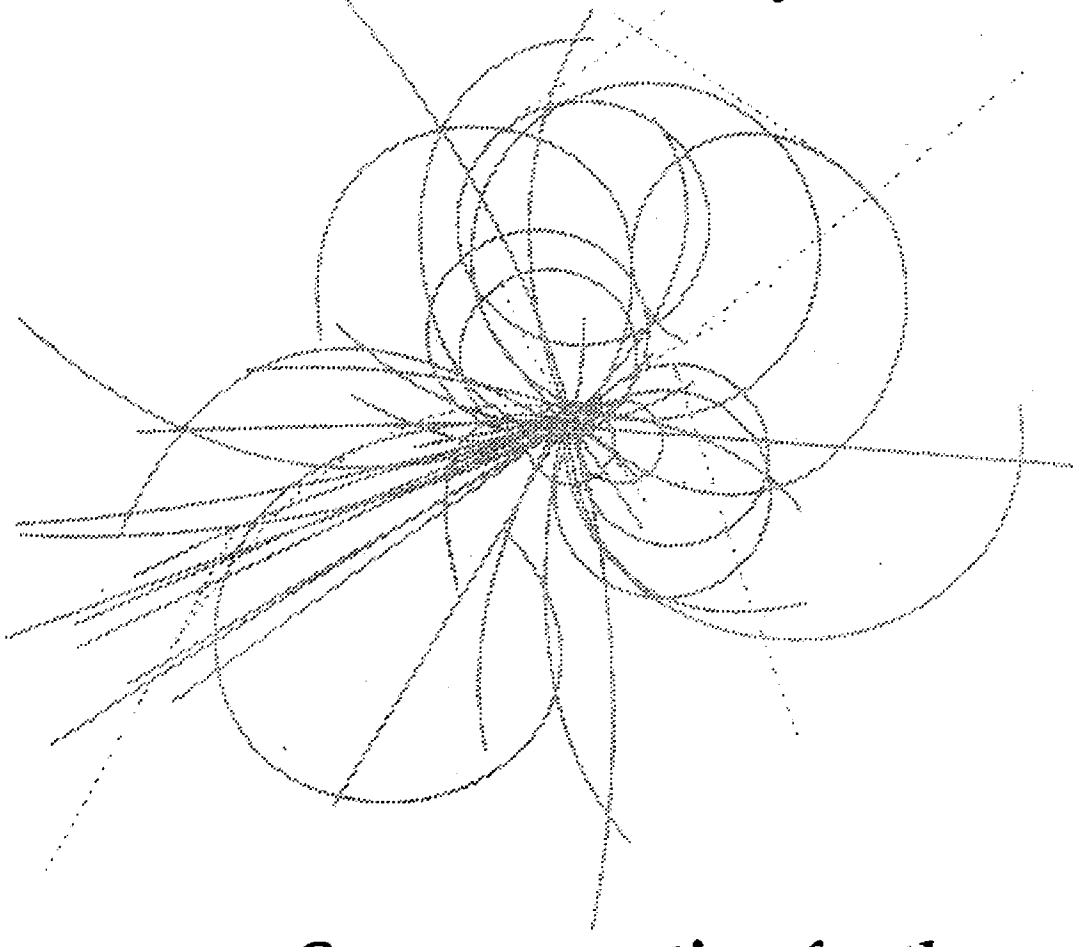
SSCL-239

Superconducting Super Collider Laboratory



Supercomputing for the Superconducting Super Collider

Yiton Yan
SSC Laboratory

Revised in February 1990

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Yiton Yan

Superconducting Super Collider Laboratory†
2550 Beckleymeade
Dallas, TX 75237

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Supercomputers are used to simulate and track particle motion for a million turns around the collider rings. These numerical studies will aid in determining the best aperture for the proton beams.

Introduction

The need to understand the most basic structure of matter requires a major advance in the energy frontier of particle accelerators. The Superconducting Super Collider (SSC), a powerful instrument currently under design, will fill this need.

The SSC will be a proton-proton collider with design luminosity of 10^{33} $cm^{-2}s^{-1}$. Its purpose will be to accelerate and guide bunches of ultra-high-energy protons into collision. Two tightly focused proton beams, each with an energy of 20 TeV, will move in opposite directions around a

racetrack-shaped orbit. As the protons collide, their constituents can interact, thereby releasing enormous energy and revealing a level of detail that has been previously unachievable. Direct evidence about the most fundamental physical forces and entities will be carried by the collision products and may be captured in the sophisticated detectors which will surround the interaction regions. Since the probability of interaction will be comparatively low, the proton beams can be recirculated to collide repetitively for many hours without significant attenuation. Thus the SSC will be constructed as a pair of storage rings capable of holding the tightly confined proton beams on closed paths for a day or more without replenishment. The rings confining the proton beams will be about 54 miles in circumference and will be housed one above the other in an underground tunnel.

A system of superconducting electromagnets will guide the protons around the desired orbit through a beam pipe. This magnetic confinement system will consist of a periodic array of bending (dipole) and focusing (quadrupole) magnets, with the bending magnets establishing the curvature of the orbit and the focusing magnets confining the protons to a narrow region within the vacuum tube. The operating cycle of the SSC will begin with the collider magnets maintained at low current for about 40 minutes while the proton beams are loaded into the collider rings from lower-energy accelerators. With injection complete, the acceleration system powered with radio frequency (rf) waves will be activated. The slow increase in the beam energy will be accompanied by a corresponding increase in the strength of the bending and focusing magnets, thus keeping the position of the beam orbit fixed while also keeping the proton beams synchronized with the accelerating system. This synchronous acceleration will be complete when the protons reach their final energy of 20 TeV. The accelerating system will then be

turned down, and the beams will be steered into collision. The resulting reactions can be studied for a day or more before the beams are depleted sufficiently so that the cycle must be repeated. During the collision phase of the operation, some of the protons will be lost due to catastrophic nuclear collisions. In addition, the dynamics of the surviving beam particles will be perturbed by the electromagnetic interaction between the two beams at each collision point.

Success of the SSC operating cycle will depend very much on the careful design of what is called the lattice, which is a detailed description of how the magnets of various sorts and strengths will be placed to form the confinement ring. The lattice encompasses both the physical arrangement and the powering or strength of the magnets. The most fundamental requirement for a good SSC lattice is that the proton beams have adequate life times. Therefore, one has to understand the motion of the protons in detail so that a suitable lattice can be designed.

A key issue of the proton beam dynamics, and thus of the SSC lattice design, is the "aperture," or the cross-sectional area within which the proton motion is stable. If this cross-sectional area is large (relative to the size of the proton beam emerging from the injector), the proton survival time will be relatively large. Clearly, one would like to have a large aperture to ensure successful operation of the SSC. This requires magnets that can provide a large region of uniform magnetic field, which in turn requires magnets that are relatively large, and therefore, expensive. Hence, the goal is to achieve the smallest possible magnet aperture (i.e., the inside dimension of the vacuum pipe container) in which an adequate space—characterized by the term "dynamic aperture"—can be identified for stable motion of the protons in the beam. Therefore, one must study the dynamic aperture for each of the

alternative magnet lattices under consideration. This is done by simulating the motion of the proton beam with numerical codes in supercomputers.

SSC Aperture Study

The confinement system to guide the protons around the desired orbit will consist basically of a periodic cell of bending (dipole) and focusing (quadrupole) magnets. This structure is called a "linear" lattice if the dipoles and quadrupoles are ideal magnets and are perfectly aligned so that nonlinear beam dynamics are negligible in the proton motion. In such a linear lattice, the protons undergo oscillations (betatron oscillation) while circulating around the desired orbit. Analytical techniques would allow an accelerator physicist to design a good linear lattice if things were this simple. However, the protons injected to the SSC rings will not all have the same momentum and so will not all have exactly the same dynamic behavior. To overcome this problem, sextupole magnets will be used in the confining system to adjust the off-momentum proton motion, and this will introduce nonlinearity into the lattice. Furthermore, practical magnets also have systematic and random errors that will induce high-order multipole effects on the proton beam dynamics. Small misalignments are also common and will affect the beam dynamics. All of these unavoidable imperfections make the SSC a nonlinear machine that requires detailed numerical studies.

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 then start short-term tracking (say, 400 turns) to study some well-defined accelerator physics criteria to predict the behavior of the accelerator.

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 desire amplitude, the corresponding accelerator design should be modified.

Generally, to study the long-term stability, one would like to track hundreds of protons (with appropriate initial amplitude distributions) element by element for millions of turns (5 minutes of SSC operation will be about a million turns). Using a current scalar computer 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, and a supercomputer is thus ideal for this purpose. One can track many particles (say, 64 protons) simultaneously, saving enormous CPU time over what a scalar machine would require. Indeed, an element-by-element post-Teapot[1] tracking program, "Ztrack,"[2] has recently been developed to take advantage of supercomputer vector processing. The codes are vectorized for multiparticle tracking and keep reducing the particle number to exclude lost

particles. One can also choose to substitute a new particle with new initial conditions for each of the lost particles so as to maintain 64 (or a multiple of 64) particles to take the best advantage of the vector architecture.

Figure 2 shows a survival plot for a million-turn tracking from Ztrack. We studied a 2-TeV injection lattice, with a 4-cm magnet aperture. The rf cavity system was turned on to maintain bunching. Two hundred and forty-seven particles were tracked with initial horizontal (x-axis) displacement amplitudes distributed between 5 mm and 12 mm with respect to the closed orbit (the distribution was not equally spaced). The corresponding initial vertical (y-axis) displacement are between 2.07 mm and 4.98 mm, which are assigned such that the effective vertical displacement amplitude would also be between 5 mm and 12 mm (there is a phase difference between horizontal and vertical betatron oscillations). Thirty-seven particles survived for a million turns. While most of the particles with higher displacement amplitudes were lost in the earlier turns, all of the particles with initial x displacement amplitude lower than 5.3 mm survived for a million turns. The dynamic aperture for a million turns is thus about 5.3 mm in radius for this 2-TeV injection lattice. Note that the dynamic aperture for a hundred thousand turns is about the same as for a million turns. Such a computation requires about 200 hours of CPU time on a Cray XMP.

Only very few cases have been carried out to a million turns. Most of our long-term element-by-element tracking effort has been for a hundred thousand turns. Figure 3 compares the data up to a 100,000 turns from Fig. 2, for a 2-TeV lattice with a 4-cm magnet aperture, with the corresponding data for a lattice with a 5-cm magnet aperture. (These new data points are shown in '*' symbol.) None of the particles with initial x displacement amplitude of less than 8.1 mm were lost. The only difference between the two lattices was

in the multiple content due to the different size of the magnet aperture. With the increase in magnet aperture, the dynamic aperture for 100,000 turns enlarged from about 5.3 mm to about 8.1 mm in radius, an advantage because this increases the linearity of the machine.

Future Supercomputing Needs for the SSC

Although one could use the survival plot in Fig. 2 or Fig. 3 to qualitatively project the dynamic aperture for longer turns, one would always question the reliability of such an extrapolation. Ultimately one wishes to track hundreds of particles for 10 million turns or more. (The lifetime of the SSC injection lattice will be about 10 million turns, while the lifetime of the collider lattice will be about 100 million turns.) Ztrack, which is a detailed element-by-element tracking code, would not be appropriate for such computations, because we know that each round of 10-million-turn tracking would take about 2,000 hours of CPU time on the Cray XMP.

Two more practical approaches for achieving SSC lattice lifetime tracking are currently under development. One approach, SSCTRK, uses a simplified lattice with fewer elements to represent the SSC lattice qualitatively. The other approach uses a program, Zmap, to extract the truncated power series map for the SSC lattice using a vectorized differential algebra library, the TPALIB, and goes on to generate the Irwin factorization map[3] for kick-map tracking (Zmaptrk). For the results from SSCTRK or Zmaptrk to be qualitatively comparable with the Ztrack results, it is expected (but not verified) that at least 1600 super elements will have to be used in the SSCTRK, or that an ninth-order map will have to be extracted for the Zmaptrk. Both SSCTRK and Zmaptrk are vectorized for multiparticle tracking. Preliminary testing shows that for 64 particles and 10-million-turn

tracking, either approach will need about 100 hours of CPU time on the Cray-2 or slightly more time on the Cray XMP.

In addition to the vector architecture that is helpful to SSC lattice design, the large memory available in the Cray-2 is also critical in extracting high-order truncated power series maps for the SSC. The TPALIB requires a large number of integer pointers to optimize the truncated power series multiplication and some other related routines. Zmap will be executed primarily on the Cray-2.

Parallel processing on multi-CPU supercomputers is currently being planned. Just as vector processing can speed up multiparticle tracking, so can parallel processors. Therefore, a multiple-processor supercomputer with an autotasking compiler would be of great value to the simulation effort. We look forward to having available a new supercomputer that has many (say, more than ten) CPUs and that is equipped with an autotasking compiler.

Summary

The success of the Superconducting Super Collider's operation will depend not only on the successful development of the superconducting magnets but also on an appropriate design of the SSC lattice. Obtaining such a lattice design for the SSC will require extensive nonlinear work, involving huge computations. In particular, to determine the optimum aperture, one has to track hundreds of protons in the SSC lattice for at least 100,000 turns. Such a computer task would be difficult or even impossible without the vector processing available in supercomputers.

Acknowledgments

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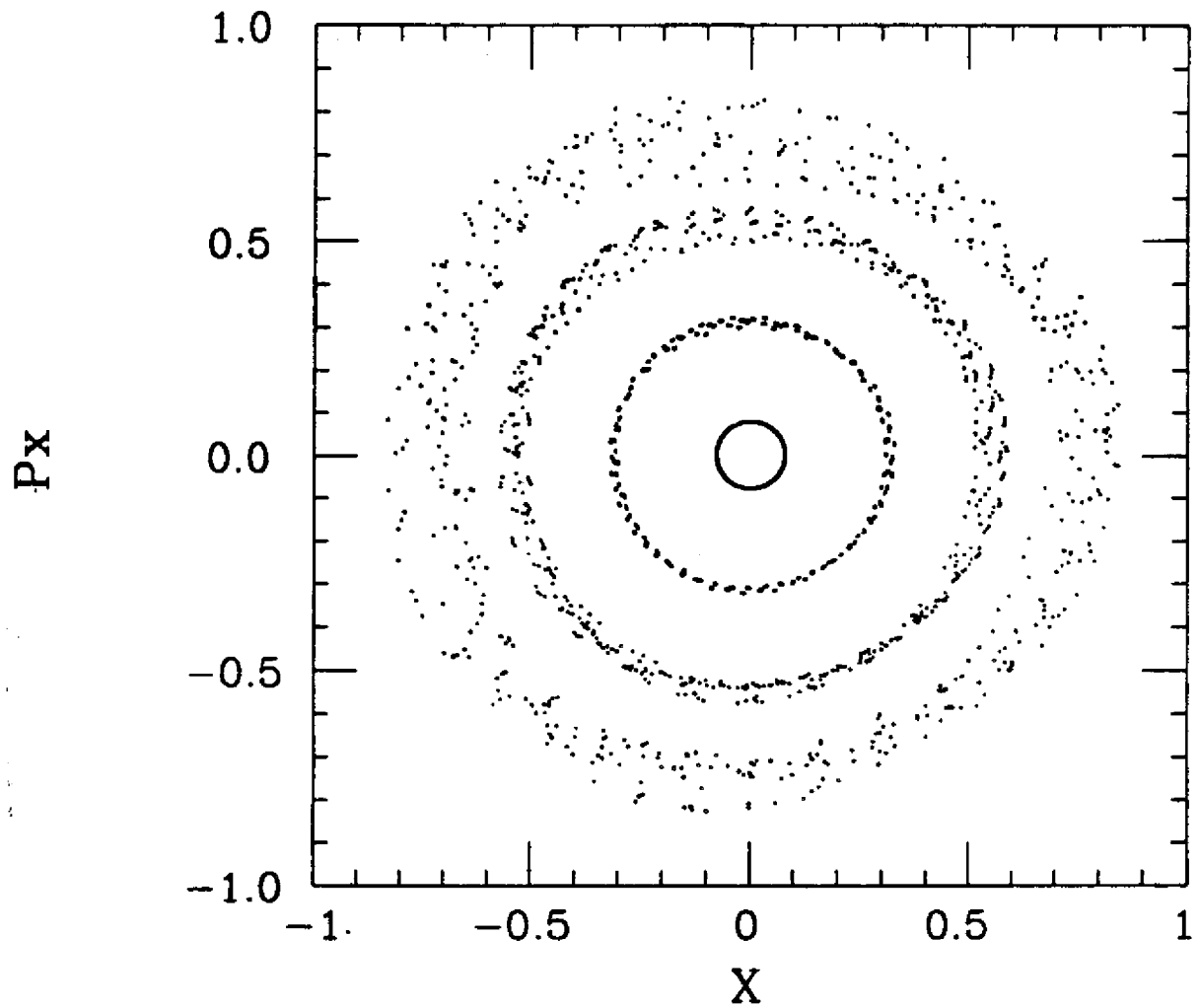

Fig. 1. Phase space plot (p_x vs. x) for four protons with different initial amplitudes, where x is a Floquet space coordinate and p_x is its corresponding Floquet space momentum; that is, they are normalized such that a proton with linear motion would trace out a circle. The variation in the amplitude 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.

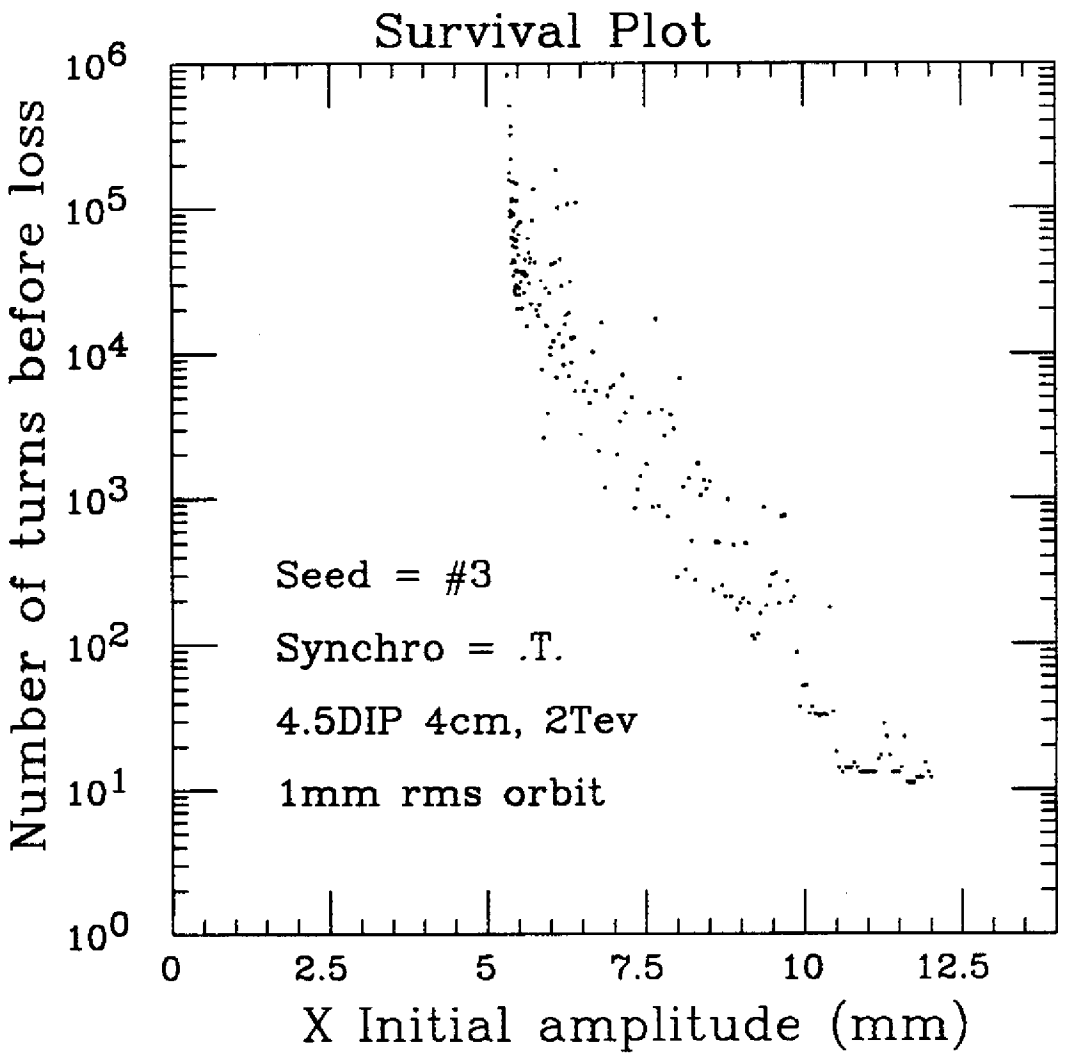

Fig. 2. A million-turn survival plot for a 2-TeV, 4-cm magnet aperture injection lattice, showing how many turns around the collider ring were made by particles of various initial amplitudes. Out of 247 particles (ranging from 5–12 mm in the x displacement amplitude), 37 particles survived for a million turns. No protons with initial x displacement amplitude of less than 5.3 mm amplitude were lost. Thus the dynamic aperture for a million turns is about 5.3 mm in radius for this 2-TeV injection lattice. (This figure shows only the protons that were lost.)

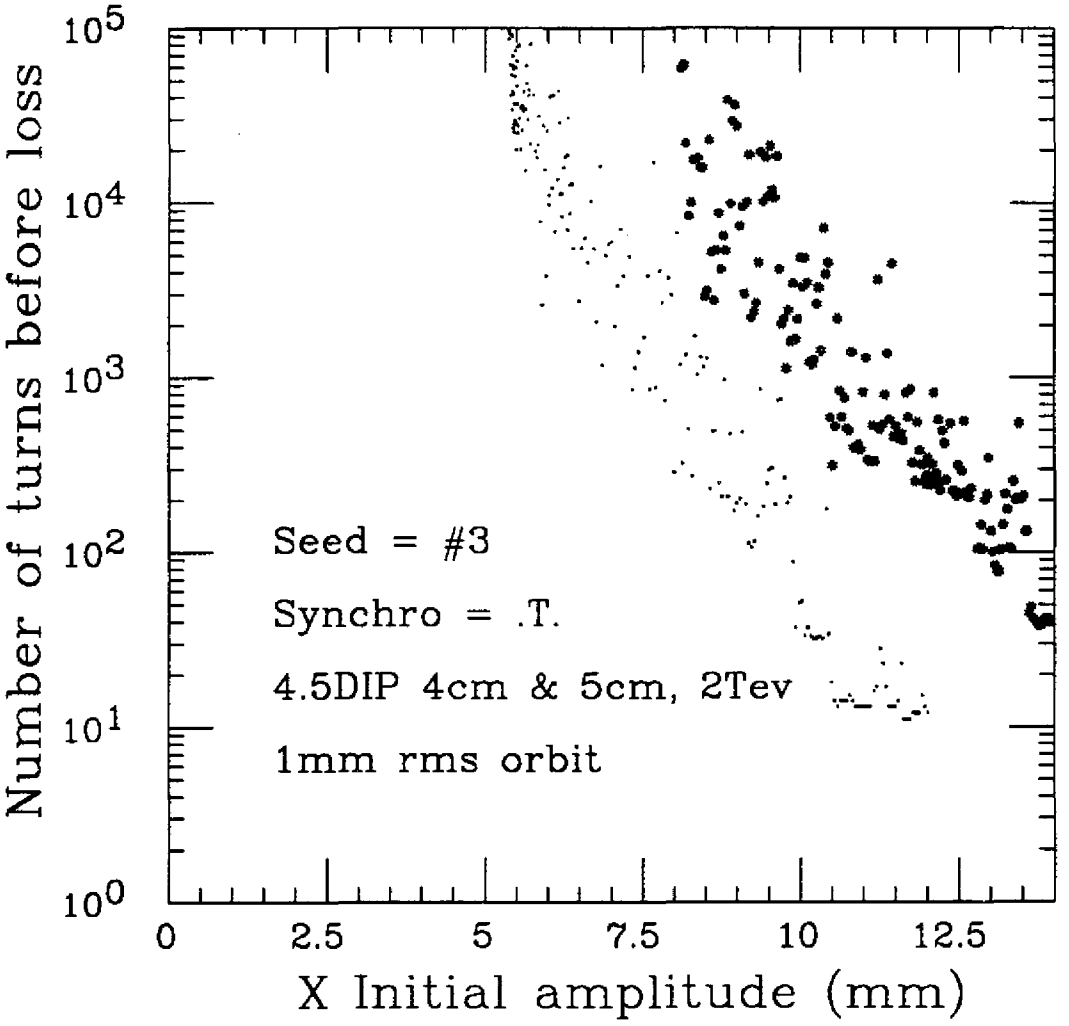

Fig. 3. A hundred-thousand-turn survival plot for a 2-TeV injection lattice, comparing the data for a 5-cm magnet aperture (shown in '*' symbol) with the data for a 4-cm magnet aperture (shown in '.' symbol and also in Fig. 2). With the 5-cm aperture, no particles with initial x displacement amplitude 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. (Again, this plot shows only the protons that were lost before 100,000 turns are reached.)