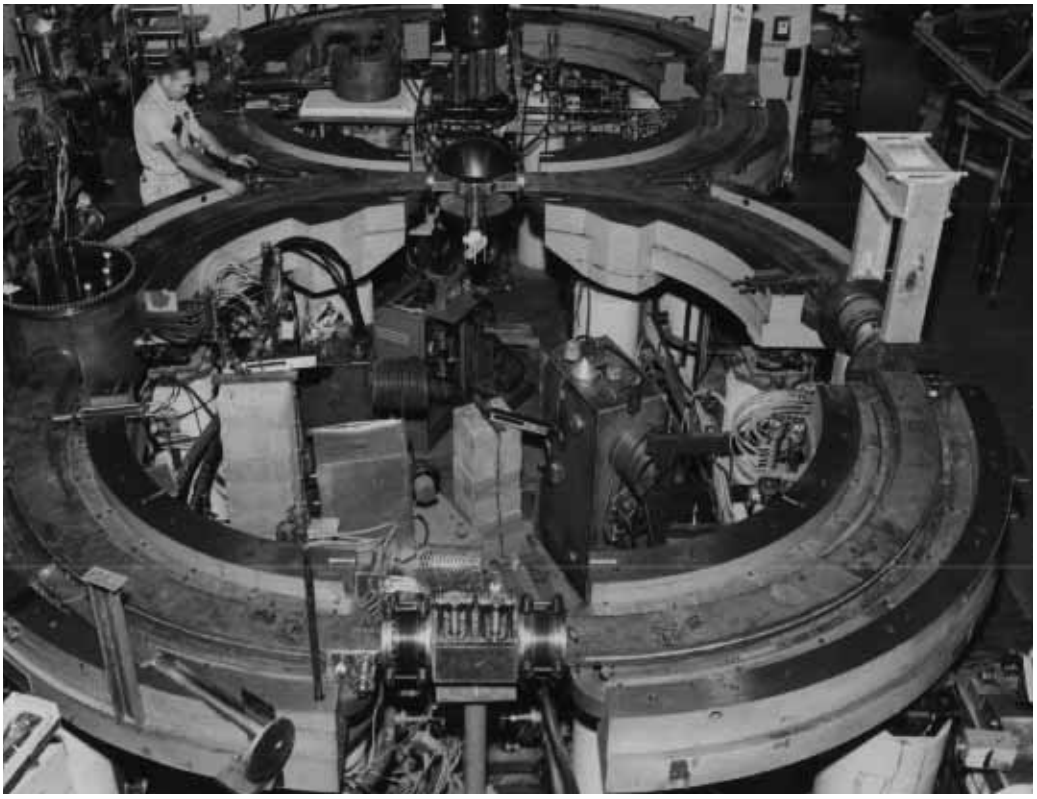

The first colliding-beam machine, a double-ring electron-electron collider, built by a small group of Princeton and Stanford physicists. (Courtesy Stanford University)

commensurate value. Of course "value" has to be broadly interpreted in terms not only of foreseeable or conjectured economic benefits but also of cultural values related to the increase in basic understanding. In view of all these considerations, the choice of the next logical step in accelerator construction is always a complex and frequently a controversial issue. Energy is but one of many parameters to be considered, and the value of the project has to be sufficiently great before a decision to go ahead can be acceptable to the community at large.

All these comments may appear fairly obvious, but they are frequently forgotten. Inventions that advance just one of the parameters—in particular, energy—are often proposed sincerely. But unless the other parameters can be improved at the same time, to generate an overall efficient complex, increasing the energy alone usually cannot lead to fundamentally new insights.

THE ENERGY that really matters in doing elementary particle physics is the collision energy—that is, the energy available to induce a reaction, including the creation of new particles. This collision energy is *less* than the laboratory energy of the particles in a beam if that beam strikes a stationary target. When one particle hits another at rest, part of the available energy must go toward the kinetic energy of the system remaining after the collision. If a proton of low energy E strikes another proton at rest, for example, the collision energy is $E/2$ and the remaining $E/2$ is the kinetic energy with which the protons move ahead. At very high energies the situation is complicated by relativity. If a particle of total energy E hits another particle of mass M, then the collision energy is given by $E_{coll} \sim (2Mc^2E)^{1/2}$, which is much less than $E/2$ for E much larger than Mc^2.

If two particles of equal mass traveling in opposite directions collide head on, however, the total kinetic energy of the combined system after collision is zero, and therefore the entire energy of the two particles becomes available as collision energy. This is the basic energy advantage offered by colliding-beam machines, or colliders.

The idea of colliding-beam machines is very old. The earliest reference to their possibility stems from a Russian publication of the 1920s; it would not be surprising if the same idea occurred independently to many people. The first collider actually used for particle-physics experiments, built at Stanford in the late 1950s, produced electron-electron collisions (see photograph on the left). Other early machines, generating electron-positron collisions, were built in Italy, Siberia and France. Since then there has been a plethora of electron-positron, proton-proton and proton-antiproton colliders.

There is another problem, however. If the particles participating in a collision are themselves composite—that is, composed of constituents—then the available energy must be shared among these constituents. The threshold for new phenomena is generally defined by the collision energy in the constituent frame: the energy that becomes available in the interaction between two individual constituents. Here there are major differences that depend on whether the accelerated particles are protons, deuterons, electrons or something else. Protons are composed of three quarks and surrounded by various gluons. Electrons and muons, as well as quarks and gluons, are considered pointlike, at least down to distances of 10^{-16} centimeter. Recognizing these differences, we can translate the Livingston plot into another chart (top right, next page) showing energy in the constituent frame versus year of operation for colliding-beam machines.

But the idea of generating higher collision energy via colliding beams