THE FLUTTERING, SPIRALLING FLIGHT OF CYCLOTRON EVOLUTION

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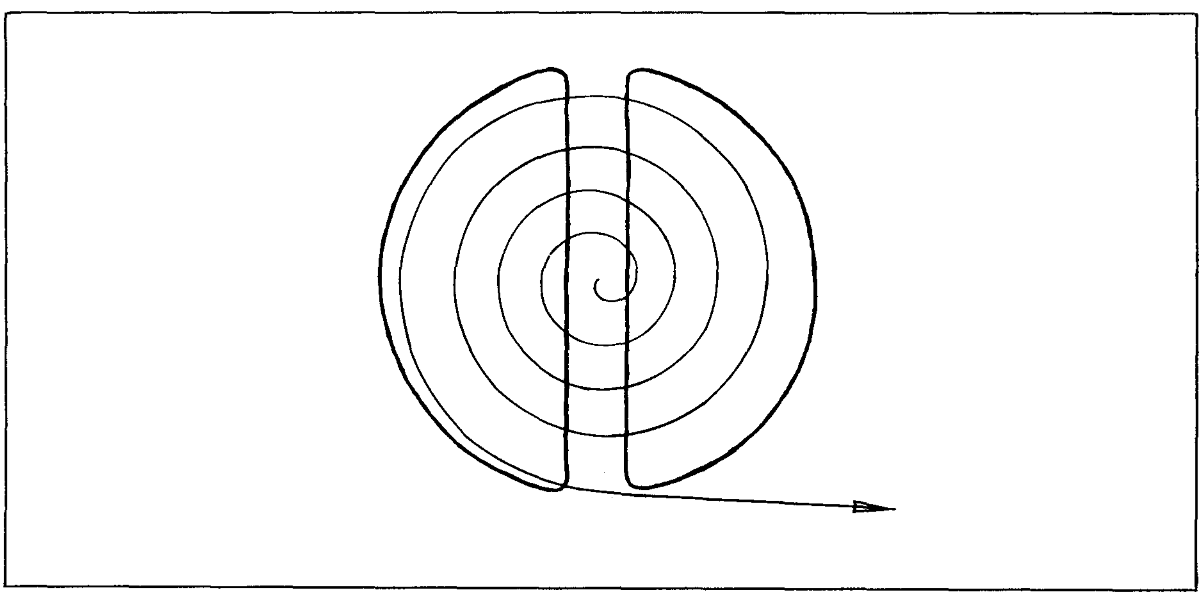
Among all the hazards of working with accelerators, I know of none more potentially catastrophic than that of serving on a conference organizing committee. Like other hazards of the most insidious sort, this one is characterized by extreme unpredictability. Outlandishly improbable events, regarded by rational people as too remote to consider, actually occur! I can think of no other way to explain the fact that I have come straight from the breakfast table to stand here before you and present an after-dinner speech. I am only a little more worried for myself than for the audience, which must listen in a very dry state, without any of the customary pre-banquet lubrication!

My assigned task is to present something originally characterized as an introductory and keynote address, containing a certain amount of historical background. This seemed plausible enough at the start, but closer study shows that it is full of pitfalls. The concept of a "keynote" implies a foreknowledge of what is to come, and a strongly unifying theme; but consideration of the evolution of cyclotrons has led me only to the concept of exponentially increasing specialization and diversity of activity in this field. Of course, this is true of everything around us. No less an authority than Professor Bernardini, in addressing the CERN 1963 International Conference on Sector-Focused Cyclotrons and Meson Factories, noted that in the period of interest he had come from the bicycle to the Caravelle as his personal mode of transportation. Since the Caravelle is an airplane, and flies, I have now answered those who wondered how the word "flight" found its way into my title.

In earlier days, meetings of cyclotron experts involved a small number of people, all of whom knew a lot about every part of a cyclotron. Prof. Heyn, of Delft, reminisced with me last night about the Sea Island Conference in 1959, attended by only about 80 people. Each could talk to his neighbor in the room, or ask reasonably knowledgable questions, about any topic under discuscussion. Nowadays we are so specialized that a conference such as this one seems to take on the aspect of a last-ditch effort to prevent centrifugal fragmentation of the field.

Another pitfall threatens anyone who tries to generate a meaningful historical summary. It is all very well to select the highlights of the Roman Empire, for example; neither Caesar nor Antony can complain to the speaker afterwards of being slighted. But to describe the key points in the history of cyclotrons to a group containing many of the people who made that history themselves will surely generate a series of minority opinions that the job has been incomplete. Being from Berkeley, where much but not all of the early history occurred before I arrived, I hope I may be forgiven for a great many omissions.

Nevertheless, I propose to briefly review what I regard as some of the important conceptual landmarks in the evolution of cyclotrons. Although I have not counted the words in my talk, you may now settle down for a lecture equivalent to well over 12,000 words, since I have prepared almost a dozen pictures, each being worth a thousand words. These pictures are designed to enable you to see the cyclotron through the eyes of others, so as to have a well-rounded outlook rather than a specialized one, and to appreciate the point of view of the various experts in this rapidly growing field.



THE CYCLOTRON AS SEEN BY THE INVENTOR

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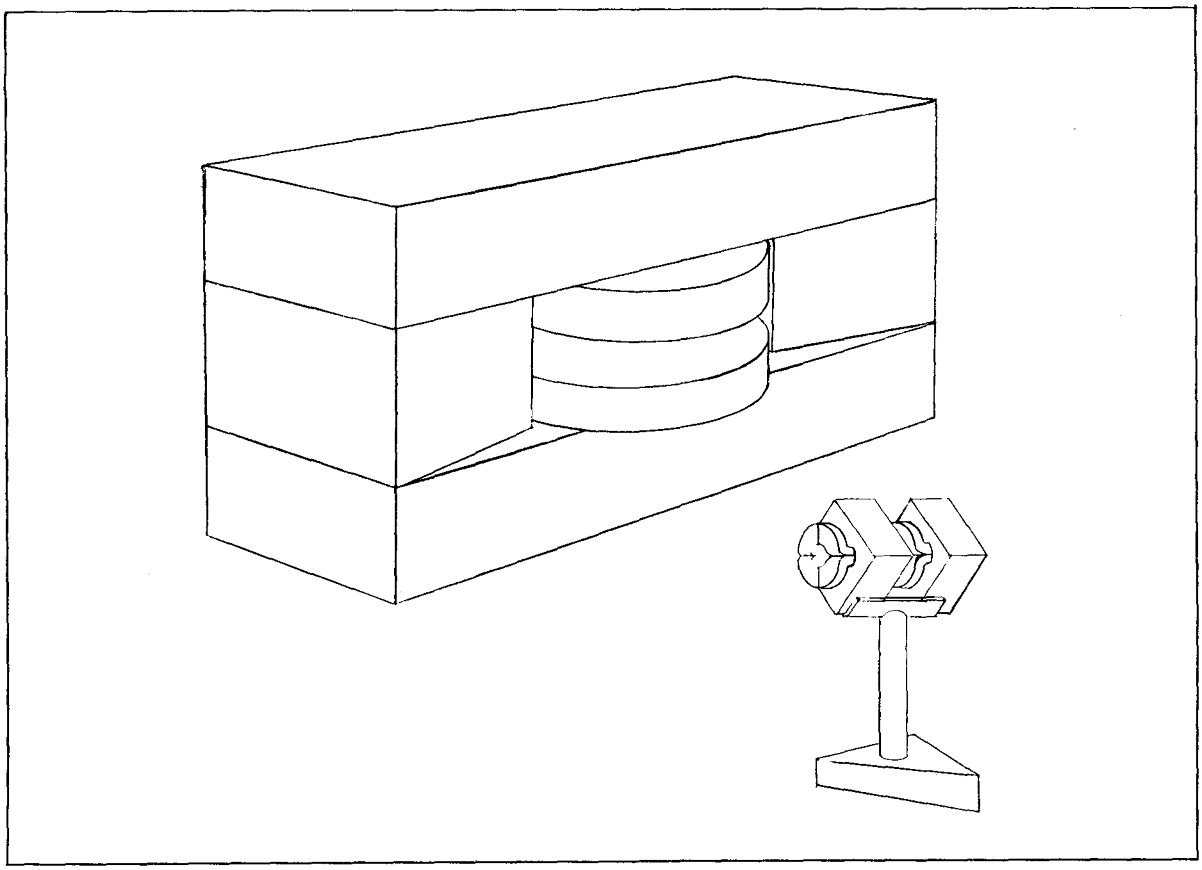
Of course, the first great landmark was the conception of the cyclotron in 1930 by E. O. Lawrence and its early development, which he and his colleagues pursued so vigorously. The second landmark I want to mention is of another type, which had a powerful influence not only on cyclotrons but on many other fields of scientific endeavor. This was the evolution by Lawrence, in the 1930's, of a form of scientific teamwork by a group of specialists that was at that time quite new in research laboratories. A key element of his achievement was the successful incorporation of professional engineers into the team. One of the very first of these, Bill Brobeck, a mechanical engineer, is with us here today.



THE CYCLOTRON AS SEEN BY THE MECHANICAL ENGINEER

Nowadays we take for granted the need for mechanical and electrical engineers in accelerator design and construction; in fact, the most recent large conference in this country on accelerators, in Washington, D.C., last year, was sponsored by an engineering society!

Now electrical and mechanical engineers have somewhat different ideas about how to do certain things, and I am reminded of one of the fruits of Brobeck's accumulated experience which he expressed to me in a very compact way a few years ago: "Never do anything electrically if you can do it mechanically!"

Be that as it may, there are things about a cyclotron that cannot be done mechanically. The electrical engineer, besides understanding radio-frequency problems, is often a comfort-loving fellow who will find time and energy not only to get the parasitics out of the oscillator but also to provide some of the amenities, such as a public address system, and a radio (requisitioned as a "wide-band signal detector") for listening to the symphony on the night shift or a ball game on Saturday afternoon.

We are all grateful for both his professional and his extracurricular ministrations. Now in addition to this difference between mechanical and electrical engineers, we observe another; the electrical man is fond of meters. Oh, of course the mechanical man will know about a water flow meter and a strain gauge, but he is really not in it by comparison. The amenities of the electrical engineer include the provision of orderly controls with lots of meters. However, he is under another kind of pressure from the physicist, who wants to be able to change everything continuously. This gives rise to the need for many switches and knobs. When I was involved in 1951 with the Berkeley electron model cyclotrons of the Thomas type that we called "cloverleaf" cyclotrons, I came to know an electrical engineer who classified each physicist by the number of knobs he wanted to have. Some were "three-knob men," and one was a "ten-knob man," but the ultimate accolade he reserved for Reg Richardson, who wanted, and got, several dozen knobs for fine tuning of the field to achieve isochronism at many radii.

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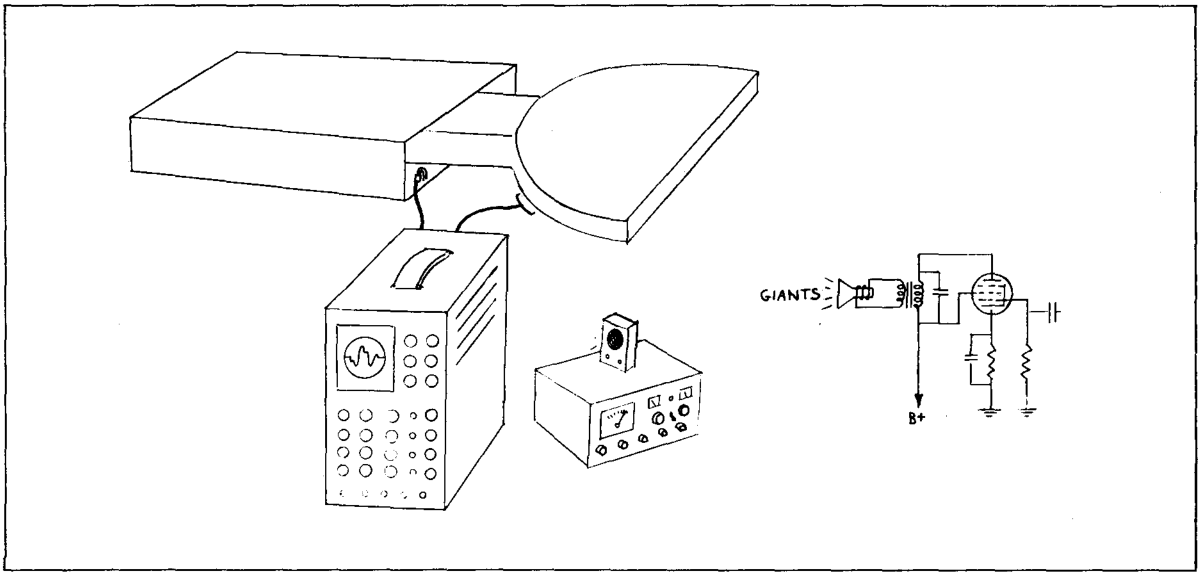
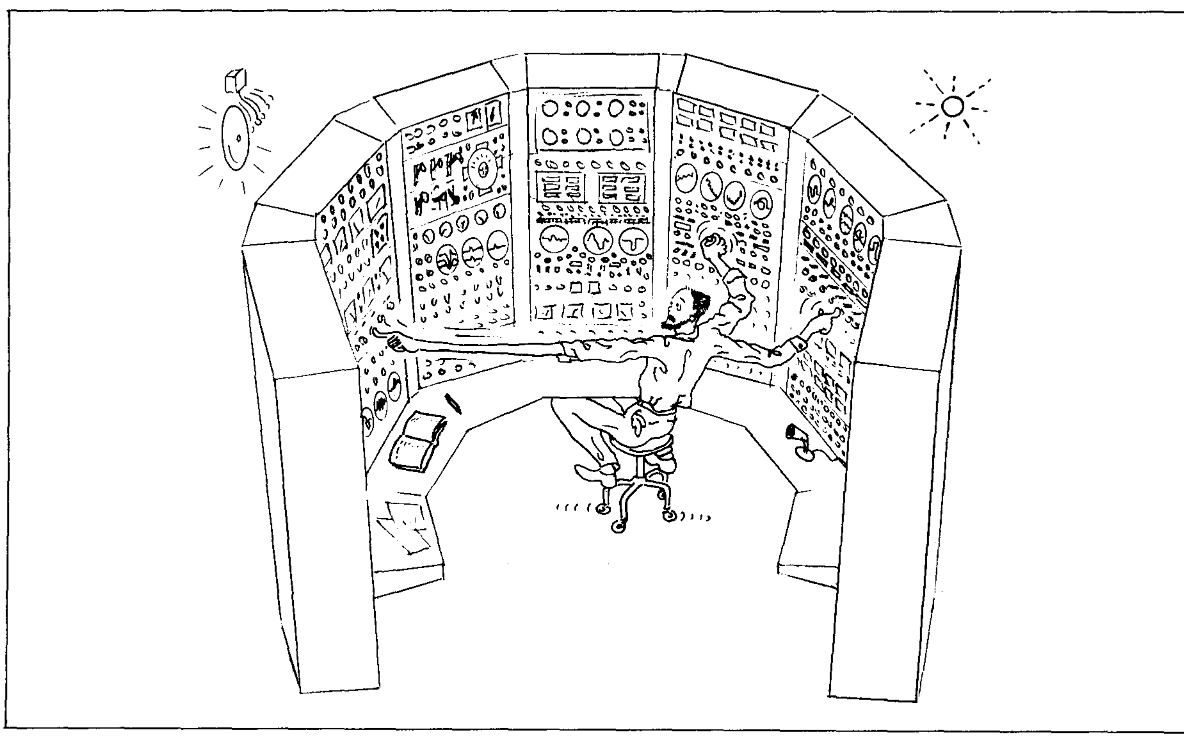


THE CYCLOTRON AS SEEN BY THE ELECTRICAL ENGINEER

The natural result of this evolutionary trend was the modern cyclotron control station. At a certain point it became evident that the thing was just too complicated for a physicist to bother with, so the regular accelerator operator entered the scene. This body of relaxed but attentive, unflappable men have had the situation under control ever since! On the airplane coming here I was told by Brobeck of discussions at Berkeley in the early days about the possibility of designing a one-button cyclotron. It was concluded that this was possible only if the button was one which called Ken MacKenzie!

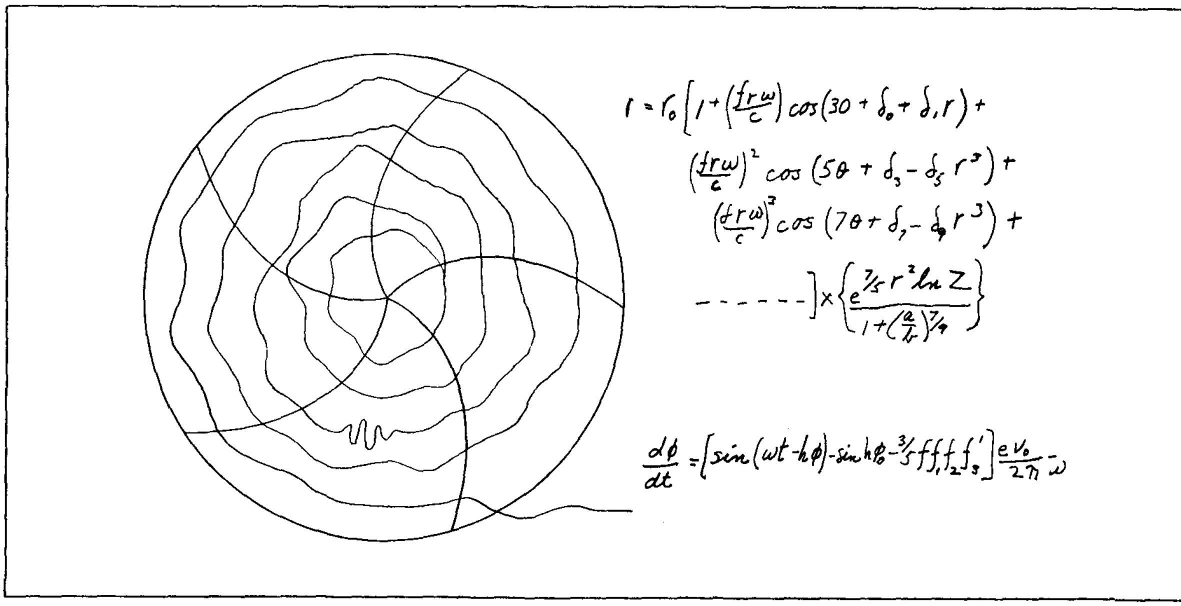


THE CYCLOTRON AS SEEN BY THE OPERATOR

Now I have gotten ahead of myself, and I must go back to the next important advance, the appearance of the theoretical physicist. Hans Bethe was the first to dig in; V. F. Weisskopf, in his opening remarks to the 1963 CERN conference on cyclotrons, alluded to Bethe's early work, stating that he had published a paper in 1936 predicting that the ultimate energy limitation of the cyclotron for protons lay at around 8 MeV. I am informed by Luis Alvarez that Weisskopf omitted an interesting detail; in the first version of his paper Bethe had quoted 5 MeV, without bothering to see what was going on in Berkeley, where 6 MeV protons were being produced at the time! This stands on a plane with the analytical proof by aerodynamicists in the nineteenth century that an airplane could never fly. Nonetheless, Bethe was the first to understand the relativistic limit and to relate it to the parameters of the cyclotron. This was an exceedingly valuable contribution.

It is interesting to observe that some of the developments on which large numbers of people are now working had their precursors many years ahead of the time at which they became accepted practice. A case in point is that of linear accelerators; Wideröe and Lawrence worked on them around 1930, but they first became really useful about fifteen years later. A most important example is to be found in the work of L. H. Thomas in 1938. Challenged by Bethe's gloomy prediction, Thomas produced the fundamental advance with which you are all familiar, the azimuthally varying field we now call flutter, a word which also found its way into the title I concocted for this talk. His work was monumental and logically complete, including as it did a prescription for achieving isochronism and orbit stability in spite of the relativistic mass increase, and even a careful treatment of multiple gap electrode systems which constitute the natural generalization of dees. The principal lack of generality was his consideration only of four-fold symmetry (he proved two-fold was unstable), but this was quickly repaired by Leonard Schiff, who published a letter (also in 1938) proving that three-fold symmetry was stable.

Now once a field is invaded by theoretical physicists and other mathematical types its flavor changes in an unmistakable way. I have some reason to believe that the care and feeding of theorists is a black art, but the establishment of effective communication between orbit theorists and intuitive experimentalists is proved by irrefutable, documented facts to have required more than a decade in the case of cyclotrons.



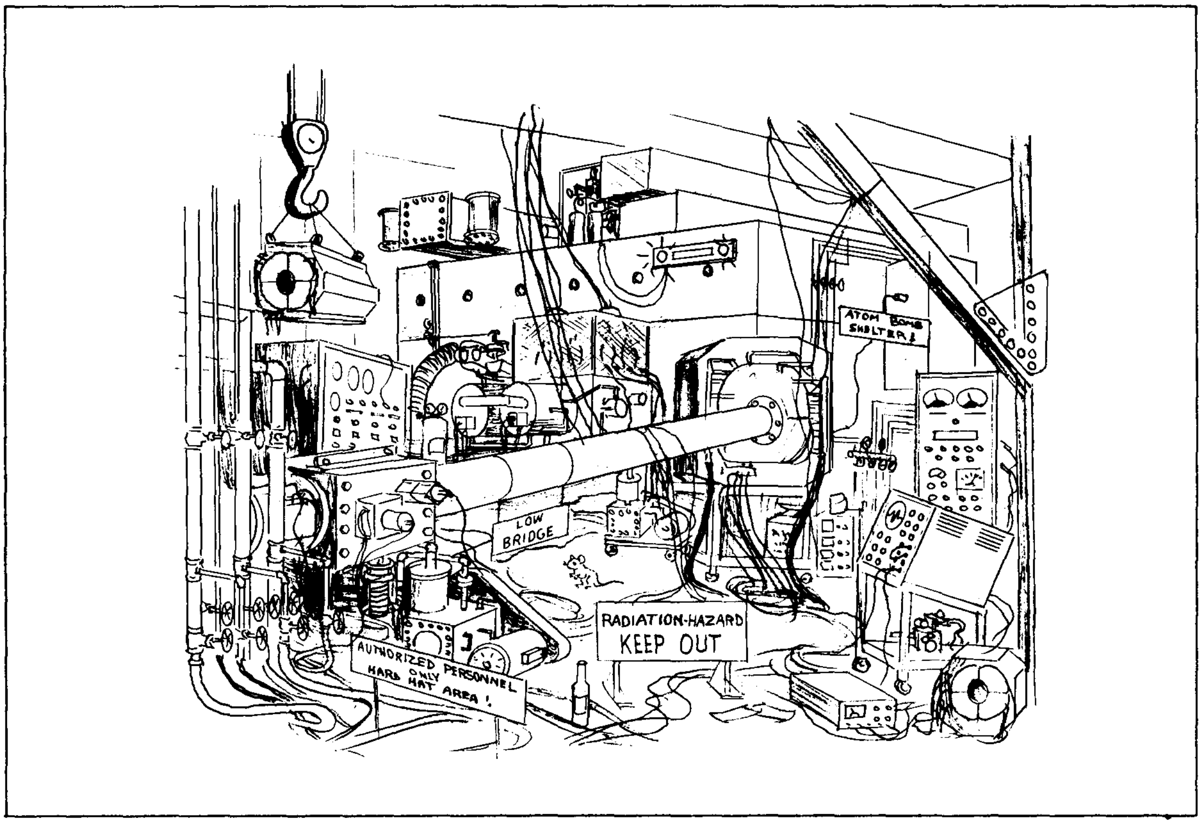
THE CYCLOTRON AS SEEN BY THE THEORETICAL PHYSICIST

It was in 1949 that Ed McMillan arrived again at the principle of Thomas, the main difference being that he considered square-wave instead of sinusoidal azimuthal variations. The time was now ripe, and progress was rapid. By about 1952 this principle had been reduced to practice in the sense that electrons had been accelerated to half the speed of light in a fixed-frequency cyclotron. At the Sea Island conference in 1959, several speakers were able to discourse learnedly about such things as phase plots and nonlinear resonances without noticeable complaints from the experimentalists in the audience.

Of course I do not mean to pass by the vitally important discovery of phase stability by Veksler and by McMillan in 1944–45; the developments which flowed from this great advance are well known to you all.

By this time the public at large, if it had not already been captivated by the drama of atom-smashing in the late 1930's, was now fully aware that cyclotrons were important, and a steady stream of visitors began to descend on our laboratories. It is never easy for us to put ourselves in the place of a lay visitor to a cyclotron.

At Berkeley many visitors receive a preliminary lecture, during which they become confused about cyclotrons, synchrotrons, synchrocyclotrons, a Bevatron, and nowadays even an Omnitron! My two sons, when they were little, used to say, "Daddy, when will you take us up to the lab to see the Trons again?" An excellent terse summary of operations at a gaily painted accelerator was once given by a guide who announced "the red thing drives the blue thing through the green thing!"



THE CYCLOTRON AS SEEN BY THE VISITOR

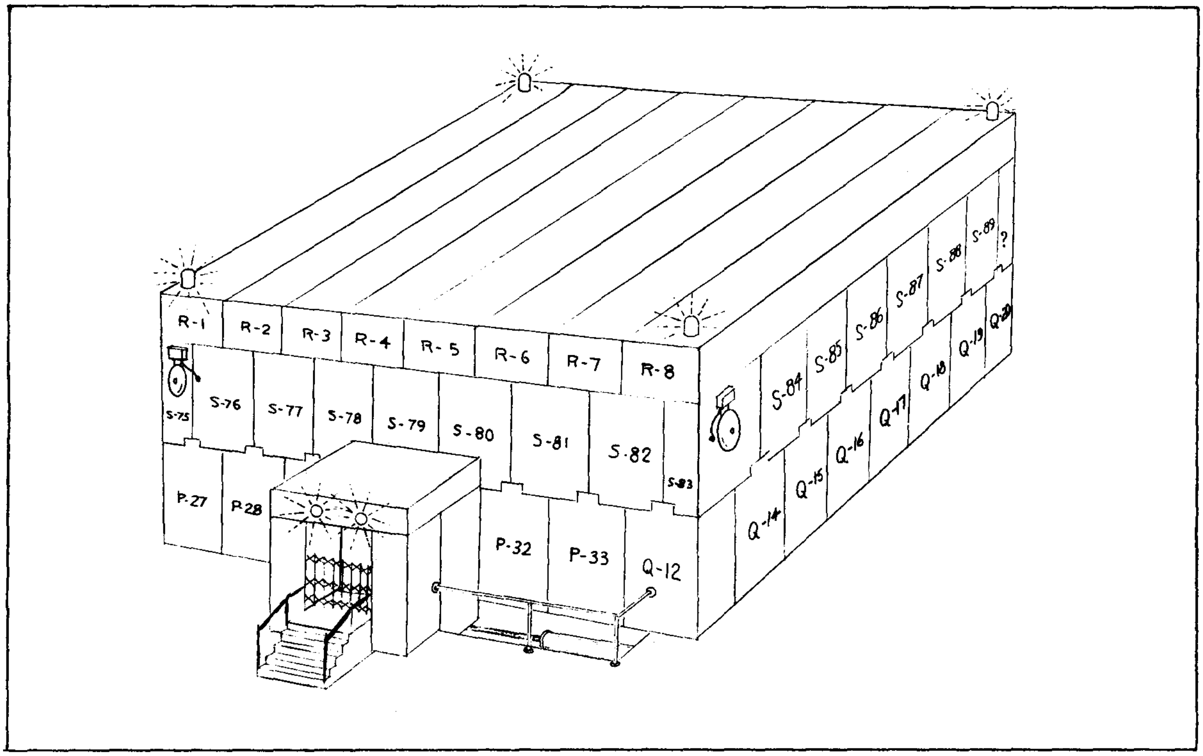
Among the landmarks along the way, I should remind you of the invention of regenerative beam extraction by Tuck and Teng and its theoretical interpretation by LeCouteur in 1951. This idea was the fountainhead from which much important work in the exploitation of resonant effects has flowed, about which we will soon hear at this conference.

The whole subject of health physics, with its concern for accelerator shielding, radioactivation of components, and so on, has received increasing attention of recent years and has been discussed at each of the previous conferences in this series; but it may have had its genesis in the middle 1930's when a mouse was placed in a thin-walled container and briefly exposed to a cyclotron beam at Berkeley to see what would happen. According to the rough estimates of that time, it was expected to receive a dose only moderately larger than most of those working in the laboratory had already sustained. However, when removed it was completely dead! A period of panic followed, which ended only when it was discovered that the air supply had inadvertently been cut off. The mouse had died of suffocation!

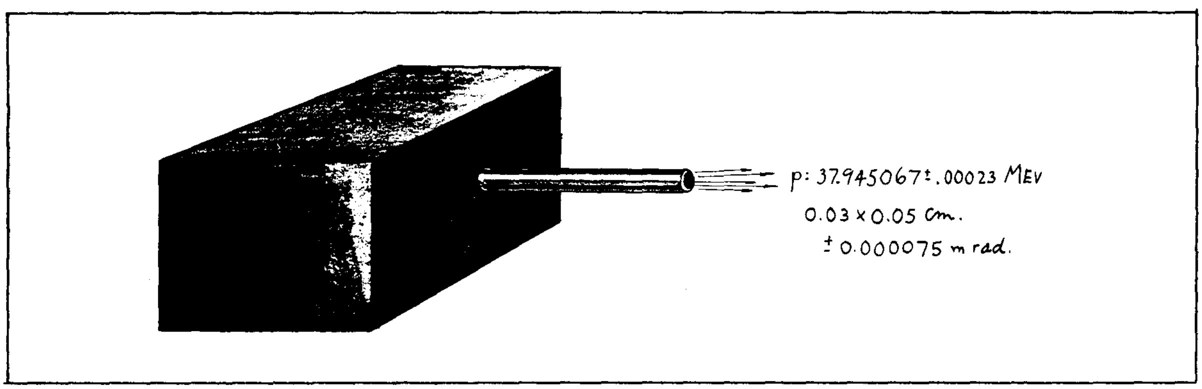
During the period after 1945 another trend began to develop. I refer to a drifting apart of accelerator builders and accelerator users; before that time these two sets of people had a very high degree of overlap. This trend further illustrates my thesis that specialization and diversity increasingly characterizes accelerator physics.

In fact, at the First National Accelerator Conference in Washington, D.C., last year, the keynote address by W. K. H. Panofsky was titled "Users and Builders," and was largely devoted to combatting the centrifugal tendency I mentioned earlier. Panofsky concluded his address with the following words: "There is a clear need for the builders to understand the problems of the users, and the users, the problems of the builders. Only if this is achieved can one hope that the conversations in the hall of the laboratory in 1980 will deal less with politics and more with science." Fortunately, at the present conference the builders outnumber the users to an extent which should prevent this problem from arising. Or will it? From my conversations at the reception last night, I am not so sure!

I must conclude my selected list of historical landmarks with one of the most important ones, so recent as not to belong in the historical past. The year 1955 was an important one, in which protons were first accelerated in a sector-focusing cyclotron at Delft. But the conceptual advance I want to emphasize is the introduction of spiralling by the MURA group, then led by Don Kerst. The concept originated in discussions between him and Keith Symon, and its subsequent development at MURA was a team effort of great value. Fluttering flight sounds inelegant, experimental, and of limited practical value; spiralling flight implies power, mastery, confidence, and control. If the analogy to cyclotron evolution is not entirely inappropriate, my title has now been justified.



THE CYCLOTRON AS SEEN BY THE HEALTH PHYSICIST

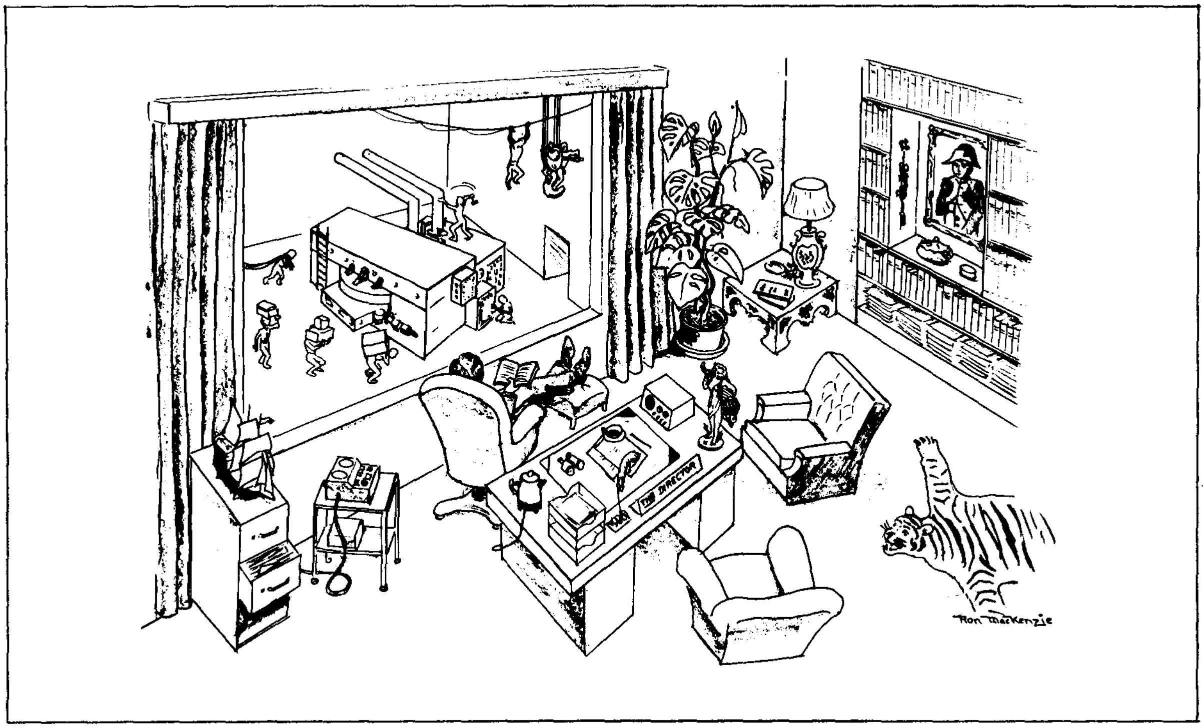


THE CYCLOTRON AS SEEN BY THE EXPERIMENTAL PHYSICIST

The cyclotron has now been seen through many eyes, but not yet through all. With the increasing specialization and diversity of effort has come a need for coordination and administration which was not felt in earlier years.

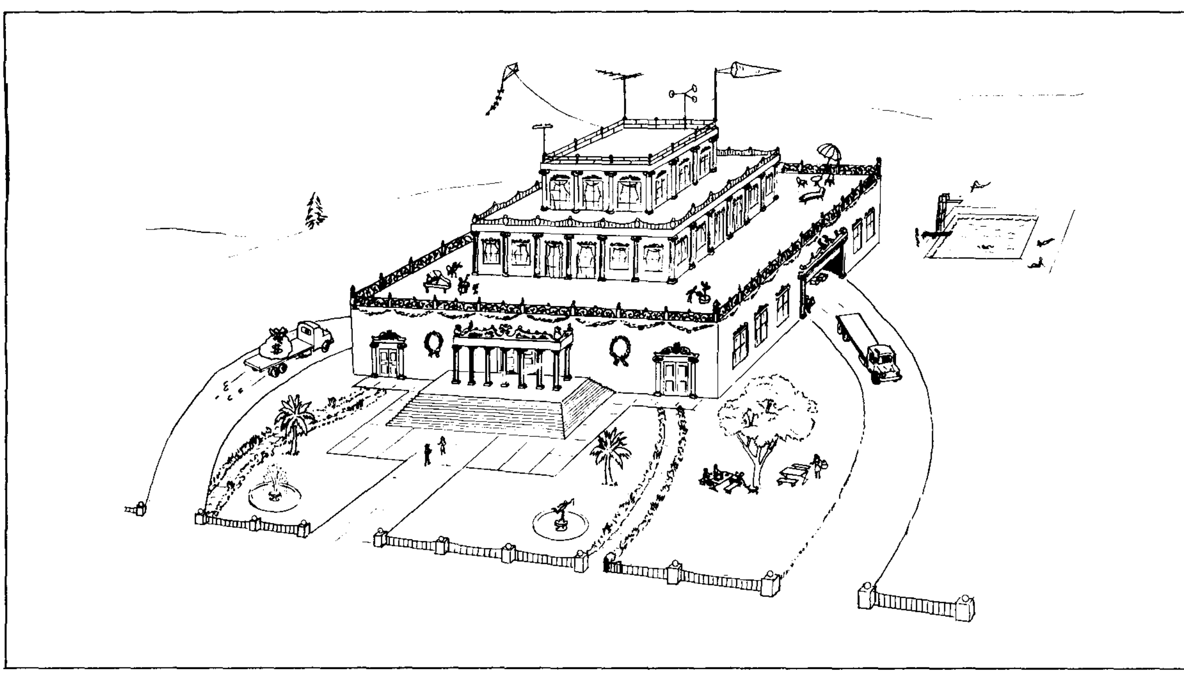
Even though my own director is not present, I feel constrained to point out that any imagined resemblance to any real director is purely accidental and coincidental!

The title of this figure should read "the cyclotron as the workers IMAGINE it is seen by the laboratory director." Of course, the director is really very busy hunting money and settling fights.



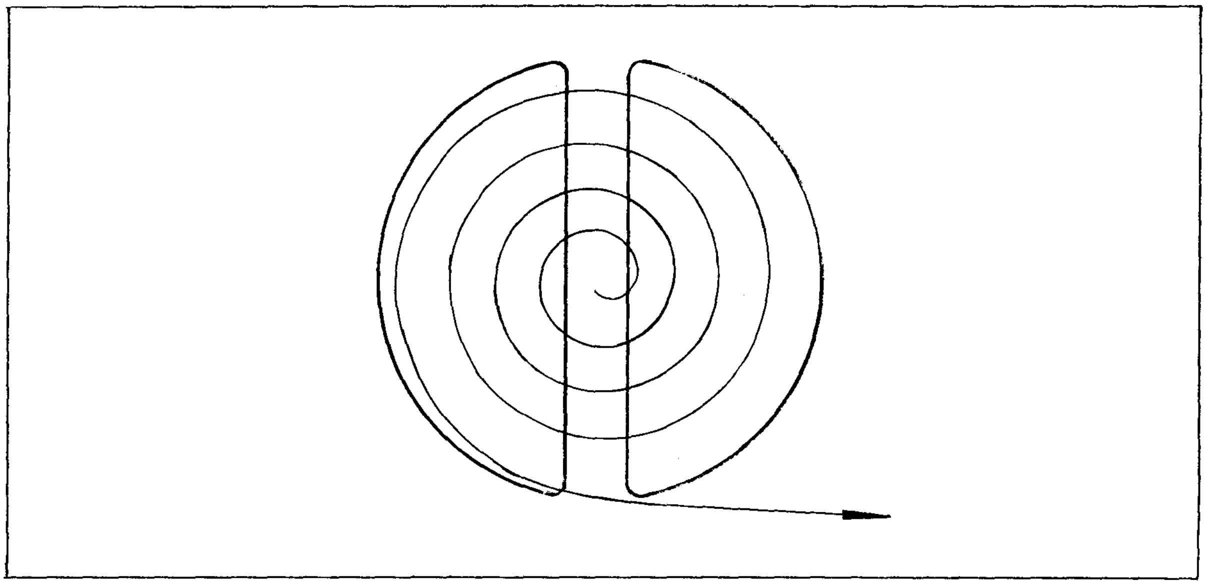
THE CYCLOTRON AS SEEN BY THE LABORATORY DIRECTOR

We must not forget the source of the largesse which enables us to cultivate this noble art. Perhaps it is as difficult to imagine how those who support us view us as it is to see the cyclotron through the eyes of a visitor.



THE CYCLOTRON AS SEEN BY THE GOVERNMENTAL FUNDING AGENCY

In concluding, I want to point out another historical connection. The drafting of these slides has been done by Ronald MacKenzie of the Lawrence Radiation Laboratory, whose brother, Ken MacKenzie, has had many years of experience with cyclotrons and who will address this conference in a later session. Finally, we all know who does most of the work in our laboratories; let us not forget the students who really make cyclotron physics possible!



THE CYCLOTRON AS SEEN BY THE STUDENT