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NEW ACCELERATORS IN HIGH-ENERGY PHYSICS*

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INTRODUCTION

First, I should like to mention a few new ideas that have appeared during the last few years in the accelerator field. A couple are of importance in the design of injectors, usually linear accelerators, for high-energy machines. Then I shall review some of the somewhat sensational accelerator projects, now in operation, under construction or just being proposed. Finally, I propose to mention a few applications of high-energy accelerators in fields other than high-energy physics. I realize that this is a digression from my title but I hope that you will find it interesting.

NEW IDEAS

The radio frequency quadrupole or (RFQ).

It was proposed in the Soviet Union during the years after 1971 that a structure could be designed in which the rf accelerating fields in a linac would not defocus the beam but could provide focusing as well as acceleration. The system would consist of four bars parallel to the particle orbits, one above and one below and one on each side. The surfaces of these bars would be lightly corrugated, the corrugations above and below facing each other and the rising part of the side corrugations facing the lower part of the upper and lower ones. There was considerable skepticism in the United States about this scheme and it was not tested here until 1978. The tests were at Los Alamos where it was shown that the Russian predictions were completely correct and that the RFQ has notable advantages at the low end of linear accelerators, being considerably cheaper and permitting materially lower injection energy.

Permanent magnets

During the past decade, pioneering work has been done on the evolution of rare earth permanent magnets. This work has been carried on in many laboratories, mainly industrial, in the United States, Japan and elsewhere. These magnets can produce pole-tip fields of up to and above 1 Tesla - ten times the useful fields of the Alnico and barium ferrite magnets of twenty years ago. I should be surprised if these magnets do not find many applications in accelerators. Already they have been incorporated in the first industrial proton linac built by the New England Nuclear Corporation in the Boston environs.

Superconductors

These find two forms of applications - in rf cavities and in magnets. Work on cavities has been in progress for many years since the early work at Stanford. There have been problems but also there have been notable successes as in the Cornell synchrotron where a superconducting cavity was used to provide the beam acceleration.

At present the major superconducting effort is on synchrotron and storage ring magnets in very high energy machines where the cost of operation of conventional magnets has been becoming prohibitive. Even including the cost of refrigeration to 4k, operating costs can be reduced by a factor of at least ten and possibly more. Development of superconducting dipoles and quadrupoles has been carried on at the Rutherford Lab in England, at the Fermilab in Illinois, at Brookhaven and elsewhere. As a result of this work which has involved working our way through some difficult problems, it is now possible to build reliable dipoles that run to 4 Tesla and quadrupoles with corresponding pole tip fields. I shall return to superconducting magnets in connection with the various high energy machines.

The linear beam collider

This is not exactly a new idea. It has been appreciated for two decades that a project for making colliding beams between electrons and positrons by setting up an electron linac and a positron linac would have some rather special advantages when they were aimed, so to speak, down each other's throats. This scheme would have no energy limit except an economic one whereas the presently favored storage ring arrangements will be limited by synchrotron radiation losses to something like 100 GeV. Storage ring costs rise very rapidly with energy where the linear colliding system costs will be linear with energy.

With storage ring systems proposed for about 100 GeV it does not yet seem time for a full-scale test of the two linac collider. But the forward-looking group at the Stanford Linear Accelerator Center is proposing a simple linear collider experiment using the present SLAC linac souped up to 50 GeV. Electron and positron beams from this linac are separated and travel through long arcs until they aim at each other. A final focus system will compress the transverse size of the beams at the collision point to about 2 microns.

Although the center of mass collision energy will be 100 GeV; considerably less than the 400 or so GeV conceived by the ultimate proponents of this idea, it is still sufficient for an initial study of the relation between the weak and electromagnetic interactions.

At SLAC this project is called the "SLAC-Linear-Collider (SLC)" Project. I think, as I shall imply by speaking of some other rather daring high energy projects, that we should wish success to this operation.

HIGH ENERGY ACCELERATOR PROJECTS

First, in our discussion of high energy accelerator projects I shall present a brief picture of the three major operations; approved, under construction, or in partial operation.

Fermilab

Fermilab has been for a decade the home of the world's highest energy accelerator, the 500 GeV proton synchrotron. During its operation two observations have been made - first, that it would be nice somehow to soup up its operation to 1000 GeV; second, that the power bill for operating the machine was out of control and would force the machine into part time operation. To answer the first observation it was

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proposed to build a superconducting magnet ring housed in the same tunnel as the synchrotron but operating at twice the maximum field of the room temperature synchrotron magnets. This was known as the "Energy Doubler". Then it was realized that operating the synchrotron at lower peak fields and carrying the beam to 1000 GeV in the superconducting ring would save a lot of power. This idea was so popular that the project changed its name to "Energy Saver/Doubler". A strong Fermilab group successfully developed superconducting magnets and began mass production. Installation in the ring began last June and should be complete early next year. It should be in full operation in the latter half of 1983.

The second phase of the Fermilab program is known as "Tevatron II". For operation at 1000 GeV, the experimental beam switchyard, and experimental areas and facilities, designed for a maximum energy of 400 GeV, will be inadequate. Tevatron II includes detailed rearrangements of the switchyard, expansion of the neutrino area and facilities, and superconducting beam switching magnets. This is now a fully authorized construction line item. Its total cost is estimated at about $60 million.

The third phase of the Fermilab program is known, for historical reasons as "Tevatron I". It is a proton-antiproton colliding beam project.

A little background is necessary to comprehend this. How does one generate an antiproton beam with respectable characteristics? The antiprotron beam generated when a high-energy proton beam hits a target spreads in all directions and is a spray rather than a beam. This problem has been solved in two places by procedures that have come to be known as "electron cooling" or "stochastic cooling". The first, evolved at Novosibirsk in the USSR, involves running an electron beam parallel to the antiproton spray - for reasons probably not obvious to the amateur, the electron beam will absorb the radial antiproton motions and convert the proton spray into a respectable beam. The second scheme, invented at the CERN Laboratory in Geneva, involves detecting aberrations of the beam and feeding back a correction signal. I do not understand why this procedure works but, apparently, it does. In America, the Fermilab has pioneered in exploiting both of these schemes and both will be built into Tevatron I. Many modifications to Fermilab synchrotron operation are required including addition of cooling rings. Both proton and antiproton beams will be stored in the superconducting 1000-GeV ring which is where the beams will collide. Evidently this operation calls for entirely different experimental approaches from those when the high-energy beam was extracted. The experimental apparatus must surround the synchrotron chamber in which the collisions will take place.

After the various cooling operations both beams will be accelerated to 1000 GeV before observations of collisions.

ISABELLE

I now turn to our colliding beam project at Brookhaven. ISA stands for "Intersecting Storage Accelerators" - the BELLE is descriptive.

This project is aimed at observation of collisions between high-energy protons. Unlike proton-antiproton beams which can be accelerated in the same vacuum chamber, proton-proton colliding beams must be accelerated in separate vacuum chamber-magnet systems which intersect at intervals. This is the basic system pioneered in the ISR at CERN.

ISABELLE was proposed in 1971. At that time it consisted of two accelerator-storage rings supplied with protons from the 33 GeV AGS. Both beams were to be accelerated to 200 GeV and proton-proton collisions could have an available center-of-mass energy of 400 GeV. The circular beam paths were to be maintained by superconducting magnets operating at fields of 4 Tesla. We already had a good deal of experience with superconduction magnets and had produced rather elegant magnets that performed nicely at 4 Tesla.

Our troubles began when we were persuaded to raise the final energy to 400 GeV. At 4 Tesla the ring would no longer fit on the Brookhaven site. So the superconducting magnet field was arbitrarily raised to 5 Tesla. Our magnets were able to reach this field sometimes, or not at all, certainly not reliably. We went into several years of refinig our design without any complete success. Then it was suggested by Robert Palmer, one of our high-energy physicists, that we should try, instead of our single layer braid winding, the two layer cable winding evolved at the Rutherford and Fermilabs and other centers. That we did and our problems were solved. We now build magnets that perform reliably to fields safely above 5 Tesla.

During the period of magnet development, other technical problems have been brought under control. It would appear that construction can proceed without delay. But we find another fly in the ointment. In combination our cost estimates have escalated and we have elected an administration bent on saving money. For the moment, our operation, though cut back on budget, is proceeding. Various cost-cutting alternatives are under consideration, including modifications to the magnets, or possibly a change in scope of the collider itself. We have adopted the name Colliding Beam Accelerator (CBA) to denote this wider effort. Meanwhile, the machine tunnel, as well as four of the six experimental areas, have been completed. The next step is the installation of a string of magnets in the tunnel, now in progress.

Incidentally, a debate between superconducting magnet designers may be of interest. We prefer to cool not only the superconducting coil, but also the iron magnetic shield and flux return. At the Fermilab, warm iron is preferred. Opinions elsewhere are divided.

LEP

The third of the major operating high-energy physics centers that I bring to your attention is the CERN Laboratory in Geneva, Switzerland. I shall assume that you know about the SPS - the super proton synchrotron - which is a machine comparable with the Fermilab synchrotron. Also I hope that you know that it has been converted into a proton-antiproton colliding beam storage ring. Because, I shall pay no attention to those splendid developments; I want to tell you about LEP, CERN's latest sensation - the "Large electron-positron ring".

I suspect that American visitors, particularly Burt Richter, had something to do with the introduction of this idea, but it has been picked up with enthusiasm at CERN. It is to be the largest electron-positron colliding beam machine ever seen.

It started as a ring 30 km in circumference. In no way could this circle be contained on the CERN site. It had to be mostly, if not all, in France. Twelve kilometers would run through a tunnel under the neighboring Jura mountains. It was pointed out that the ring would all be underground, as is the SPS ring, and the farmers overhead would not be disturbed. Generally France was cooperative, but the inhabitants of the Jura area became worried that the tunnel would penetrate and drain the undergound rivers on which they depended for their supply of water. The CERN people commented that they too had no desire to see an underground river pouring through their tunnel. It was agreed that test walls should be driven and possible that a test tunnel should be driven into the Jura. Some of this was done; in the meantime the energy of LEP was reduced by about 10% and it was rotated toward the Swiss border so that only about 3 km passes under the Jura. For the moment the local problem appears to be solved.

Phase I of LEP, which has been approved by the CERN Council will yield 50 GeV electron and positron beams. It will cost about $500 million and should be running in 1987. The funds approved are not construction funds; the Council has merely authorized CERN to divert its operating funds and personnel to LEP Phase I. While the CERN management stews about where to cut off projects to save money and provide personnel, the LEP group dreams about a Phase II in which the electron-positron energy will be raised to 130 GeV.

In summarizing Fermilab, Brookhaven and CERN as the leaders in far-out high-energy physics, I am certainly bypassing a number of almost equally ambitious centers in the US, Europe, the USSR, Japan and elswhere. Here, at least, are a few examples.

There is a good deal of enthusiasm in the high-energy physics community for making possible studies of collisions at high energies between electrons and protons. I mention three of these.

HERA

This is the latest in a series of splendid projects proposed and sometimes built at the DESY (Deutsch Elektron Synchrotron) Laboratory at Hamburg. It is designed to collide 820 GeV protons with 30 GeV electrons yielding some 300 GeV in the center of mass.

This has been discussed with ECFA - the long-standing and influential "European Committee for Future Accelerators" and has received its approval. The German administration however, seems to have reservations about the $300 million cost of the project which they feel might interfere with Germany's commitments to CERN. It seems that this project wil not start immediately.

TRISTAN

In Japan, an important academic and institutional center is being built about 40 miles northwest of Tokyo. One of these institutes, known as KEK (Japanese for high-energy physics) already is very active. Under the direction of Dr. Suwa and, more recently, of Dr. Nishikawa the Institute has built and is operating a 12 GeV proton synchrotron. TRISTAN, an ambitious project for an electron-proton colliding beam machine was first proposed by Nishikawa in 1974. It has been studied and revised since and is now a concrete proposal. In Phase I an electron-positron ring for about 30 GeV using conventional magnets would be constructed in the largest tunnel that can be accommodated on the site. In Phase II a superconducting magnet ring for 300 GeV protons would be installed in the same tunnel.

CHEER

This is a project toward which one must feel kindly, however it turns out. CHEER stands for "Canadian High Energy Electron Ring". Physicists all across Canada have been frustrated over the fact that there is no way for Canada to be in the first rank in high-energy physics. Some have solved this by joining American or European groups at Fermilab, SLAC, Brookhaven or CERN. The University of Toronto is a member of the university group that administers the Fermilab. But the more agresscive physicists wanted to be more in the picture. Hence a pan-Canadian group proposed construction of a 10-GeV electron-positron ring for installation tangent to the Fermilab synchrotron. It seems that this will not be approved. It seems, however, that a similar project is certain to evolve and that a number of Canadians will be part of the effort.

APPLICATIONS

At this point I am going to diverge from my assigned title and bring to your attention a few of the ways that the accelerator technology, developed for high-energy physics, has strayed into and contributed to other technical fields.

Intense neutron sources

For studies of the effect of 10^{14} neutrons per second on the "first wall" of a fusion reactor the only really effective source is a continuously operating 35 MeV, 100 mA deuteron linac. Dissociation of the deuterons in a target will yield neutrons with the same energy as those from a D-T fusion reaction. This project, initiated at Brookhaven, led to a design study jointly organized by Los Alamos and the Hanford Engineering Laboratory. It is known as FMIT. I believe that this operation is temporarily suspended, but it must be revived in time to provide essential information for the design of fusion reactors.

Intense neutron sources in the form of linear accelerators for one or two GeV with high intensity have been studied for a variety of purposes. For example the SNQ is a spallation neutron source proposed jointly by Karlsruhe and Julich in West Germany. 100 mA of hydrogen ions will be accelerated to 1.1 GeV and accumulated in a storage ring. Finally they will be released to deliver 10^{14} protons to a target in 0.6 microseconds.

Another application for GeV proton beams of high intensity was recognized in the early 1950's at the highly secret MTA project at Livermore. This was a Lawrence-Alvarez scheme for making reactor fuel by converting U^{238} to plutonium. A prototype was successful though something of a monstrosity because of the somewhat primitive state of the rf art. The project was cancelled because of the discovery of unexpectedly large deposits of uranium. But, with much advanced technology, and the depletion of our uranium supplies, this project has been resurrected. In particular it has been studied at Brookhaven and at Chalk River in Canada.

Synchrotron radiation sources

In 1945, when it was first realized in the United States, that relativistic electrons confined to circular paths will radiate throughout and away beyond the optical spectrum an amount of energy that rises with the fourth power of the electron energy. The conclusion was that this was only a nuisance that would set an upper limit to energy achievable in electron synchrotrons. Only in the last decade has the usefulness of the radiated spectrum been appreciated for studies of the surface and volume properties of materials. The leader in this field has been the University of Wisconsin which has built storage rings with the sole purpose of producing synchrotron radiation. Since then parasitic synchrotron radiation facilities have been attached to high-energy physics electron accelerators and storage rings, for example at Stanford and Cornell. We, at Brookhaven, have undertaken construction of a "National Synchrotron Light Source" (the NSLS) to be a dedicated source of far ultraviolet and X-radiation. It will include two storage rings, one for ultraviolet radiation, operated at 700 MeV, and 2.5 GeV ring which will put out about 400 kW of hard X-rays. Our user group includes many university solid-state physicists and chemists and also representatives of industry - the Bell Labs, IBM and others. Also we have interest among the oil industry. It is their belief that surface studies may yield information about the mechanism of catalysis which is of great importance in oil refining. The NSLS is built and is coming into operation.

Medical applications

Finally I should like to bring your attention to a few of the ways in which the apparatus of nuclear and high-energy physics has been brought to bear on medical problems.

Electron linacs have long been used in hospitals for radiation therapy and radiography. In the United States alone over 1000 electron linacs in the 4-50 MeV range are in use.

Neutron therapy is favorably regarded because neutrons are rather easily produced. By now something like 3000 patients world-wide have been exposed to neutron therapy.

But both photons and neutrons share the disadvantage that they do not have a definite range in matter. Hence ion irradiation is of considerable interest. This has been the subject of detailed study at the Lawrence Berkeley Laboratory. The study initially involved irradiation of a number of patients with an alpha-particle beam from the 184" cyclotron which, as those of you who are old enough to know, was, in its day, the pioneering instrument in high-energy physics. More recently heavier ions at very high energies (GeV per nucleon) have been produced at Berkeley by a somewhat weird combination of the HILAC (Heavy Ion Linac) and the Bevatron (formerly the 6 GeV proton synchrotron with which the antiproton was discovered). Heavy ion tumor irradiation is regarded at Berkeley with considerable optimism.

The most attractive particle, apparently, for irradiation is the negative pion. Its life is terminated when it comes to rest and encounters a nuclear particle of ordinary matter. At this point it is annihilated in a tiny explosion. On its way through matter it does relatively little damage but, on an atomic scale, its final annihilation is relatively destructive. It has a definite range depending on its energy. Hence it should be very effective in destroying tumors without doing too much external damage.

The possibility of a pion irradiation facility has been explored at some length by Dr. Henry Kaplan at the Stanford University Hospital and a proposal has been submitted to the National Cancer Institute. Approval has been postponed, however, pending results from experiments using a pion beam from the 800 MeV Los Alamos Meson Facility. There some 200 patients have been irradiated. Whether or not one has made a cure, can be known in five years or more.

CONCLUSION

As I warned you, I have diverged a bit from my assigned topic. My major aim has been to inform you about the mad schemes of which the high-energy physics community is dreaming. But a strong secondary motive that boils up inside me is that this powerful group to whom I am speaking should appreciate the effects and potentialities of the technology that has evolved during the instrumentation of high-energy physics.