COLLECTIVE EFFECT ACCELERATORS AND THE CHALLENGE OF ATTAINING ULTRA-HIGH ENERGIES*

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Abstract

Collective effect accleration concepts are very briefly reviewed with an eye to their relevance to the acceleration of particles to ultra-high energies.

I. General Remarks

It is easy--but, I think, it would be wrong--to dismiss collective effect accelerators when considering how one might attain ultra-high energy particles. For, to date, collective effect accelerators, firstly, have not accelerated light ions to more than a few tens of MeVs and, secondly, are just table-top toys, at least in comparison with the current-generation and next-generation of high energy accelerators.

But it would have been wrong to have dismissed Lawrence's first cyclotron (5 inches in diameter) or--for that matter--most anything when it was first realized, such as Edison's light bulb or Bell's phone. But is the comparison a fair one? Certainly, at the time Edison did his work, gas-mantle lamps were widely used, very effective, and had a reasonable lifetime, while his lamp was--if not a joke--certainly a table-top toy. Still, one can argue that the comparison is not proper because the

* This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, of the U. S. Department of Energy under Contract No. DE-AC03-76SF00098.

concept of collective accelerators has been around for a number of decades--but one notes that was also true of electric light bulbs. One could continue, however, by noting that millions of dollars have already been put into collective accelerators (in contrast with the development of the electric light bulb), but I think this only shows that the subject of collective effect acceleration is more difficult than that of electric light bulb technology. In short, I feel the comparison is a fair one.

But, if I feel the comparison is fair, then it seems that I believe that collective effect accelerators will--someday--accelerate particles to ultra-high energies. Well, I didn't really say that. I am not sure that the laws of nature allow collective effects to be used effectively and efficiently to attain very high energies. But I do feel strongly that collective effect accelerators should be vigorously pursued--more than they are at present--so that if they are advantageous we shall be ready to use them.

In fact, so little effort (at least by comparison with what I think is needed, not in comparison with what Edison put into light bulbs) is currently going into collective effect accelerators that we shall not know for decades and decades whether or not collective accelerators can accelerate particles to very high energies. The present world-wide effort is not, in my judgement, cost effective: a 20 TeV machine--if not the next device to be built certainly a device to seriously consider--and probably this is a regional accelerator--will cost, if "conventional" superconducting technology is employed, about $\$3 \times 10^9$. Thus one should spend for research in each region of the world--just to be cost effective--(say) $\$10^7$ over (say) 30 years. Current spending in the US on collective effect accelerators is (about) $\$2 \times 10^6$ per year, and in Europe the spending rate might be close to zero. I would hope that we scientists are motivated by a deeper interest in nature than cost effectiveness, but my point is that even by this standard we are not doing very well.

Can collective accelerators accelerate particles to very high energies? Certainly not at this time. Do they have the potential? Well, some do and some don't. I would like, in this report, to review, briefly, the ideas behind collective effect accelerators and then examine those that seem to have the potential of accelerating particles to very high energies. But dismissing a particular accelerator realization can be quite deceiving; a good idea can come along tomorrow and completely change one's thinking. So, I would like to keep the discussion general and differentiate between acceleration concepts and accelerator realizations. Perhaps in this way we will have a sufficiently elastic framework into which we can fit new ideas as they--inevitably and most wishfully--come along.

Collective effect accelerators have been reviewed in many recent articles and books.[1-8] These treatments vary; some emphasize the basic physics,[4,5,7] while some summarize the present status of the field.[1,2,3,6,8] What the world does <u>not</u> need is another review article. (What it <u>does</u> need--and this remark should not be in parentheses--is more original research on collective effect accelerators.) The interested reader can readily obtain--and he will find quite readable--one, or more, of the referenced review papers. Thus, although a review of collective effect accelerators was presented at this conference, the author is--understandably, he hopes--unwilling to create still another lengthy review article re-covering the work of Refs. 1-8. The present article is brief and limited to a discussion of general concepts and the possible relevance of various approaches to the attainment of ultra-high energies.

II. Collective Effect Acceleration Concepts

The motivation for developing collective effect accelerators has been described in the review article I wrote (Ref. 5). I can think of nothing more effective than simply quoting from that article:

"In non-collective accelerators, the charge and current of the accelerated particles is small, or at best a restriction on the performance of the device. Thus, to fair approximation,

$$\nabla \cdot \mathbf{E} = 0$$

$$\text{and} \quad \nabla \times \mathbf{B} - \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} = 0. \qquad (1)$$

In collective devices, on the other hand,

$$\nabla \cdot \mathbf{E} = 4\pi\rho,$$

$$\text{and} \quad \nabla \times \mathbf{B} - \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} = \frac{4\pi}{c}\mathbf{J} \qquad (2)$$

which opens up a world of possible configurations. In fact, as we shall see, there are a great many configurations which have been proposed for collective accelerators and one of the problems is to categorize the various approaches and to limit activity to those few which appear easiest to achieve or most advantageous if realized.

In conventional accelerators the $\underset{\sim}{E}$ and $\underset{\sim}{B}$ fields are produced by external conductors and hence are limited by the properties of those materials. Thus the performance of these accelerators (accelerating gradients and/or bending radius; i.e., size) is limited. Collective effect accelerators, on the other hand, can have much higher fields than conventional accelerators [because of Eq. (2)] and hence give the promise of being compact and, possibly, cheap.

Of course, one must make the ρ or $\underset{\sim}{J}$ which is employed to create the $\underset{\sim}{E}$ and $\underset{\sim}{B}$ fields of collective accelerators. As we shall see, the production of ρ or $\underset{\sim}{J}$ requires a significant device and hence--as presently envisioned--collective devices are not as attractive as one would at first think.

Nevertheless (ignoring collective instabilities) one cannot help but feel that the removal of the constraint of Eq. (1) should allow the design and development of very attractive devices. This has been, and remains, the fascination of collective effect accelerators."

To date, there have been four different categories into which all schemes for the collective acceleration of particles may be put. Firstly there are charge clusters (such as are employed in the Electron Ring Accelerator, the Collective Focusing Accelerator, or the Plasma Ring Accelerator.[9]). Secondly, there is the moving potential well concept (such as in the Beam Front Accelerator, or the Ionization Front Accelerator). Thirdly, there are moving waves on electron streams (such as in the Autoresonant Accelerator, or the Converging Guide Accelerator). And fourthly, there is the use of intense laser beams to organize plasma motion (such as in the Beat-Wave Accelerator).

to invent schemes than it is to study the schemes experimentally, and this is especially true since the schemes that have been proposed have been rather complicated.

On the other hand, some schemes have been investigated by many scientists for many years. Perhaps the record belongs to the Electron Ring Accelerator, which has been under experimental study for more than 15 years. In second place is moving-potential-well-acceleration which has been known, and under investigation, for more than a decade.

In another talk, presented at this conference, detailed description has been given of the Electron Ring Accelerator scheme along with a discussion of the present status of this concept. Similarly, detailed descriptions have been given, in other talks, of some of the other collective effect acceleration schemes and the present state of each of them. The reader is referred to these papers for details--which really is what it is all about--of the various schemes.

Not all of the collective effect acceleration schemes--each of which has at least been mentioned in Sect. II--has been covered in the specialized talks at this conference. On the other hand, at least one example of each of the four categories, mentioned in Sect. II, is covered in some detail. The reader interested in learning about schemes which have not been covered at this conference is referred to the review papers which have been cited. (This information is not up-to-date, but because this field is so inadequately funded, progress is quite slow,and hence the old information is not so old.) But, the reader will be able to obtain quite a good idea of the present state of collective effect acceleration by reading the detailed papers of this conference proceedings.

IV. Collective Effect Accelerators and the Quest for Ultra-High Energies

Collective effect accelerators do not--yet--produce particles of very high energy. Yet the potential is there.

Conventional accelerators employ external fields to manipulate and accelerate particles to high energy. Collective effect accelerators, in contrast, employ external fields to manipulate and accelerate a collection of particles (often electrons) which then, in turn, accelerate those particles which really interest us (often protons or ions) to high energies. Thus, collective effect accelerators form a whole new class of accelerators, which are at least, and probably very much more, complicated than conventional accelerators.

In fact, it is the complication of collective accelerators which has resulted in the very limited successes achieved to date. Yet, there would seem to be possibilities associated with the complexity of collective accelerators which could be decidedly advantageous when exploited. It would seem very premature--and probably it would be wrong--to dismiss the whole class of collective effect accelerators as being uninteresting. We simply do not know enough to eliminate any of the concepts; more work on each of them must be done before our understanding is sufficiently advanced to allow us to make firm statements.

Yet, collective effect accelerators are difficult to make and to operate and thus we need modest goals so that work upon these accelerators will continue. Thus, it makes sense to attempt, firstly, to accelerate ions to modest energies (for nuclear physics, industrial, or medical applications). Subsequently can one attempt to attain really high energies.

Alternatively, one can attempt to employ collective effects--but not a "collective effect accelerator"--to enhance the performance of conventional accelerators and, at the same time, gain some more experience with the fine art of particle handling. The Wake Field accelerator and the Free Electron Laser as a Power Source are two examples of suggestions which fall into this category (see Ref. 6).

Finally, it should be noted that we are becoming ever more sophisticated in the manipulation of particles. This sophistication is as a result of our attempts to attain other goals, such as very high current accelerators, fusion energy by means of magnetic confinement of plasmas, or fusion energy by means of heavy-ion or laser implosion of pellets. Surely, this increased sophistication will, someday, result in practical collective effect accelerators. I would be surprised if the sophistication didn't result in a very high energy accelerator and, conversely, I would be surprised if the quest for ultra-high energies did not, eventually, incorporate collective effect accelerators.

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All of these schemes for the collective acceleration of particles have their difficulties. One must, in the first case, form cluster of charge and there are, as one can readily suspect, limits to this process. In fact, the history of this category of accelerators consists of the detailed study--both theoretically and experimentally--of the creation and manipulation of charge clusters. In fact, almost all of the work so far has been put into the problems associated with making charge clusters of the requisite density and size (rather than into the acceleration of the clusters).

The second category, namely the moving potential well, has the problem of control of the speed of the well. A great deal of effort has gone into this subject.

The third category--waves on beams--has associated with it the problem of growing the desired wave to large amplitudes (without having the undesired waves grow or become large due to non-linear coupling) and then controlling the speed of the desired wave.

The fourth category has many problems associated with it for it involves a rather dense plasma (which surely is unstable) and laser beams which, probably, cause side-scattering phenomena. We know little about this subject, however, and therefore we are not even in a position to list, not to say study, the various problem areas.

III. Collective Effect Accelerator Schemes

A large number of accelerator schemes have been proposed through the years; in fact, many more schemes have been proposed than have been experimentally realized. Essentially this is because it is much easier

DISCUSSION

(The published talk is not the same as that delivered at the meeting. Nevertheless, a number of relevant points made in the discussion are given here).

Adams. Do any collective devices hold out hope of getting more than 100 MeV/metre?

Sessler. There is a hope of achieving high energies. So far we have learnt how to accelerate particles using external fields only. I cannot believe that in the next 50-100 years we shall not learn how to go the next step, but I cannot point the way just at the moment. When you remove the restrictions $\rho=0$ and $j=0$ from Maxwell's equations you should be able to do much better!

Johnsen. The basic ideas were known in the early 'fifties, and are older than, for instance, the AG principle.

Sessler. That only proves that it is harder!

Motz. The beat-wave accelerator seems to be on the way to providing the required MeV/metre, but have ways been devised to stack it?

Sessler. There are other more fundamental physical aspects such as transverse effects which have not yet been looked at, but there is hope that this problem can be solved.

Richter. You need not only energy but also good optical quality. Which of these collective effect gives both?

Sessler. The only thing that looks at the moment as though it might have a significant application to high energy physics is the beat-wave accelerator. Another alternative is that perhaps one can learn to control the ionization front accelerator; this has not yet been done.

Winterberg. I believe that in a dense plasma you may get multi MeV energies, but it is difficult to see how in a plasma of density 10^{17} particles /cc you can get multi-terawatt energies. A plasma in general is very messy.

Willis. A comment on the last three questions. It is certainly true that the laser plasma accelerator works on collective effects. On the other hand all the others are based on the idea that you can persuade a plasma to do what you want it to do, whereas experience shows that it does what it wants to do. I would put the laser driven system in a different category because we can make light waves do what we want them to do with great precision. In the beat-wave accelerator there still is some plasma physics. Looking at this six or seven years ago I suggested using the leading edge of the plasma wave, so that causality guarantees no unpleasant modes. This demonstrates the attainment of high gradients with full accuracy, no plasma effects, and accurate staging. This may not be a practical accelerator, but shows that the problem has 'in principle' solutions.