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RECENT WORK ON THE DUBNA COLLECTIVE ION ACCELERATOR

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The main steps on the collective method of acceleration development in Dubna and the present situation of this work have been described in this paper.

During the past years physicists working on accelerating problems came to understand evident difficulties which arise when creating accelerators for ultra-high energies. And though, as before, accelerators for energies about 1000 GeV were designed, decisions to build those accelerators came to life with greater and greater complications. Now it seems clear that 1000 GeV is the energy limit for the classical accelerators. Further rise of energy requires principally new methods of acceleration in which the effective fields acting on the accelerated particles would be increased substantially.

In 1956 V. I. Veksler pointed to the possibility of new mechanisms of acceleration making use of collective effects. The fundamental idea behind such methods is that the field which causes the particles to be accelerated, is not produced directly by external sources but by the interaction of the accelerated particles with another group of charges, a jet of electrons, plasma flux or electromagnetic radiation.[1] These methods are characterized by the fact that under certain conditions the field intensity acting on the particle, is proportional to the number of particles.

The principles of collective acceleration suggested by V. I. Veksler were presented at numerous conferences and in papers. However, until now the possibilities of these methods have been estimated with great caution. This was explained above all by the lack of exact propositions as to now to obtain and to keep the dimensions of the bunch of charged particles.

Numerous obstacles concerning plasma instabilities which once influenced greatly the development of nuclear fusion automatically, and as a rule but of place, were brought to the collective accelerators. The Dubna group searching for models of accelerators based on collective effects met a complicated problem not only to base the possibilities but to prove the reality of such accelerators. The approach taken to solve this problem considered all these factors. And though nowadays it is just of historic interest, it is worth regarding the main steps of the work. All the fundamental possibilities of making a bunch have been considered from the certain point of view in the so-called 'accelerating approximation', which at the very first steps made it necessary to regard one of the bunch components as relativistic. Due to the stability demand for a bunch an annular form proves to be most profitable. To provide maximum field strength inside the bunch, a compression method has been used. It was based on the adiabatic change of bunch parameters in an increasing magnetic field. So there appeared the scheme of obtaining an electron bunch, which was grounded fully on the traditional accelerating approach and had nothing to do with plasma. Adding an ion to the electron bunch naturally changed nothing. The initial development of the method was performed in 'one ion approximation'. The respective modelling[2,3] proved the correctness of those understandings and assured us of the possibility of creating an accelerator working by collective principles. Further researches on the questions concerning the influence of ions on the ring showed that those ideas are true even for great concentrations. It allowed us to work out all of the basic systems of the would-be accelerator. This method being developed, a number of new possibilities of creation of various accelerators for protons and other ions including the heaviest ones have been discovered. Hence, as once the autophasing principle allowed us to create almost all types of modern accelerators, the collective method will give the opportunity to build some types of accelerators too. Careful studies of this principle carried out in Dubna just after the first large discussion at the conference in Cambridge[4] fully changed the common view and nowadays a lot of scientists all over the world are working at the problems of the collective accelerator.

Now let us observe certain steps of work on collective acceleration in Dubna.

In the variant given above of making an electron-ion bunch, the electron beam at a certain radius (injection radius) forms a ring. Then this ring is adiabatically compressed in the slowly increasing azimuthally symmetrical magnetic field and the ring electrons are accelerated by the induced electric field. At the end of the compression, ions are injected into the ring. A number of experiments concerning the stationary state of an electron ring and the process of its adiabatic compression have been performed. The time intervals we are interested in are substantially small as compared with the time of establishment of a Maxwellian distribution in the cross-sectional direction. Particle densities are not large. So examination has been carried out at the approximation of the self-consistent field without collision integrals being considered. In Ref. (5) using the simplest distribution function, which in the case of the stationary azimuthal uniform state depends only on two integrals of motion, the relativistic equations describing azimuthally uniform self-consistent fields have been obtained.

In Ref. (6) in certain approximations these equations are solved and give the expression for the particle density of the ring bunch, limited in space. An expression for the minor radius of the ring with approximately round cross section has been obtained. The gradient index of the external magnetic field necessary in this case has been found.

We found it possible to make a nonlinear solution of the self-consistent problem of formation limited in space, using only appropriate for this problem small parameters of the relation between small and large dimensions of the particle bunch.[7]

This work gave the possibility to create a theory of electron movement in the compressor which is in good agreement with experiments. The first model showed the correctness of the fundamental ideas of electron movement in the process of adiabatic compression, but the poor electron source used in this experiment failed in obtaining the required bunch density.[8,9] In the process of work at the model great attention has been paid to identification of the threshold of the longitudinal instability in the electron beam at injection,[3] which was regarded at that time as most dangerous for the dense electron bunches.[10] However, further calculations with screens taken into account showed that the instability threshold is high enough and for our cases this instability does not occur.[11]

All these investigations allowed us to make a device where the electron-ion bunch with the necessary parameters has been obtained.

An opportunity of resonance passing has been provided in this device. A further difficult step concerned work on the ring extraction. Successful investigations in this work required two main problems to be solved—to create a system destroying one of the 'stoppers' in the magnetic field, where the electron ring in its final state of compression is placed and to make it possible to avoid the resonance at $\nu_r = 1$.

At the final state of the compression an electron ring is placed in the magnetic well of the adgesaton (adiabatic generator of charged toroids), which is formed by a system of coils symmetrically arranged around the plane in which compression of the electron ring takes place. In this state the electror ring is loaded with the number of ions required This takes place due to the ionization of the neutral gas by an electron beam. Any types of ions may be used. The storage process and requirement for the accelerating field for any ions have been examined in Refs. (12) and (13). Studies of particle movement in fields which are spatially nonuniform show that an annular bunch such as described above will move in the direction in which the field decreases. The velocity of the bunch will increase together with the decrease of the azimuthal velocity of electrons:

$$\beta_z = \beta_{\perp 0} \sqrt{1 - H_z/H_{z0}}.$$

Consequently to extract the electron ring magnetic barrier must be removed and the de creased magnetic field must be created. It must b remembered, however, that the gradients of thi field must not exceed the limit at which ion detach ment begins. Such observations performed for th real movement of an annular bunch[14] lead to th following conditions for the gradients:

$$\frac{\partial \beta_z}{\partial z} = \frac{2\gamma_{\parallel 0} m_\perp}{R\gamma_\parallel^2 M}\left(1 + \frac{N_i}{N_e}\frac{M}{m_\perp}\right)\epsilon_{\text{Coul.}}$$

In this expression

- $\gamma_\parallel$ is a relativistic factor, corresponding t the longitudinal velocity of the ring,
- $\gamma_\perp$ corresponds to the velocity of tl electrons moving along the ring,
- R is the ring radius,
- $m_\perp M$ are masses of an ion and an electron,
- N_i, N_e are the total numbers of ions an electrons,
- $\epsilon_{\text{Coul.}}$ is the Coulomb field.

It must be noted that this limitation is true for times larger than the period of ion oscillations.

As is shown by thorough calculations for small times, this magnitude can be overcome and the conditions given above must be fulfilled only in average for the time of ion oscillations. To extract the electron ring we have three additional coils which are not powered at the initial moment. At a specified time those coils are powered. This time is chosen so that, though the field in the main coils continues to rise, the effect of the additional coils makes an induction field, weakening the magnitude of the field in the place where the barrier is maximum and even removes it. Calculations have been done[15] and the results have shown that the potential well of the magnetic field is removed successively at the distance of 10–12 cm from the mean plane. This system has been built and is in good agreement with calculations. However, technical guarantee of such a system did not prove to be enough because of the large dynamic loading of the additional coils. Later on, to extract the ring, we used a system combining shunting of the main coils placed on one side of the mean plane. So all the fundamental experiments on the extraction of the electron ring and its acceleration have been performed with this system. Nevertheless, the system described above is not good enough to extract and accelerate the electron ring loaded with ions. As the electron ring is extracted from the compressor the potential well is decreasing and at the end disappears. In such a system of extraction due to the decrease of the external well the ring comes into a state when oscillation frequency is equal to $\nu_r = 1$. Hence because of the resonance acting on the particles the parameters of the ring change greatly and the ring can blow up. To avoid the dangerous influence of the resonance it is necessary to traverse very quickly the region $\nu_r < 1$ to the region $\nu_r > 1$ (in a time of order 10^{-9} sec) or to stay all the time in the region $\nu_r < 1$. After thorough discussion of the possible way to use those variants the second one has been chosen and tried. The requirement of holding $\nu_r < 1$ through extraction and acceleration provided the necessity to create a well of magnetic or electric field in all the regions of the ring movement. It is equivalent to the use of focusing forces. The questions of focusing have been viewed by us from the beginning. Certain possible ways of focusing have been considered.[16] First of all was autophasing on the travelling wave. However, following this way as the ring is accelerated, the gradients are falling, so with reasonable field intensity of the travelling wave focusing is possible only up to $\gamma = 4$. The same limits appear when the azimuthal component of the magnetic field is used for focusing the moving ring. Beginning with certain velocities of the ring movement the azimuthal component of the field influences substantially the magnitude of the large radius of the ring.

The Miller mechanism of focusing on opposed waves has also been thoroughly examined. But this method is effective only for high γ.

So besides great technical difficulties all these methods are not universal for all energies of the ring.

Even when regarding questions of creating a bunch the interaction of the electron current with the screen was taken into account.

Interaction of the charged bunch with the screen is of a 'coherent' effect, i.e., the force acting on each particle is proportional to the total number of particles. It is interesting to know that the screening can be used for ring focusing. Let us take a straight charged rod formed by the electron flux and screened by a metal conducting plane. If the distance between the center of the rod and the plane is substantially larger than a small dimension of the rod, then the image field can be replaced by the field of the infinitely thin beam, formed by the charged particles of the other sign. The elementary distribution of the interaction forces of the 'imaged' rod with the boundary particles of the real one gives the focusing force. The magnitude of this force would be far smaller than the repulsive Coulomb forces of the particles in the beam, if there were no longitudinal movement of the particles. As a result of this movement the repulsive forces in the beam are weakened γ times and there is a possibility to compensate the Coulomb repulsive forces by the image forces. A rod, moving as a whole in the direction perpendicular to the particle movement inside the rod can be a model of a ring, flying in the screen tube. But in this case the electric field of the rod becomes dependent on time which results in appearance of the screened magnetic field weakening the focusing forces of the image γ times, and makes them smaller than the defocusing ones. To use image forces for focusing seems to be very attractive, as this way of focusing does not require additional power and does not depend on the ring velocity for high enough γ. Therefore, certain attempts have been made to find the systems which would hold the focusing effect of the electrical screening and decrease the defocusing effect of the magnetic one.

First of all it appears that when considering a ring screened by a cylinder, the curve gives the desired result and to neglect the curve in the self fields is possible with the following inequality:

$$\frac{1}{\gamma_{\perp}^{2}} \gg \frac{a^{2}}{R^{2}} \ln \frac{8R}{a}$$

and in the induced fields with the inequality:

$$\frac{1}{\gamma_{\perp}^{2}} \gg \frac{b-R}{R} \ln \frac{R}{b-R}$$

i.e., it is possible to create conditions under which self field can be regarded as 'straight' (which means weakened γ times) and induced as 'curved' (non-weakened). Here:

a is the minor radius of the toroid ring,
R is its major radius,
b is the radius of the shield tube.

But the holding forces in this method are not sufficient. It was necessary to find a configuration of the screen where the reflective capacities for the electrical and magnetic components would differ greatly. As a result of detailed investigations such a system has been found. It represents a cylinder slotted along the axis. For such a system reflection coefficients of the electrical and magnetic fields are essentially different. With a reasonable number of slots the reflection coefficient for the electrical field is close to 1, while for the magnetic one it differs slightly from 0.[17] So it is possible to choose the dimensions of the system in such a way that along the whole length of the extraction system the holding forces are kept constant and hence $\nu < 1$.

So both of the problems of extraction and preliminary acceleration of the electron ring with ions have been solved and the former results on acceleration have been obtained.[18,19] When regarding different variants of the system, accelerating the electron ring loaded with ions, a number of its peculiarities have been considered:

(a) A ring represents a compact formation with a large charge. The natural current, produced by this charge (up to tens of thousands of amperes), heavily loads the accelerating system.

(b) Rotational movement of the electrons makes the ring effectively heavy, therefore its acceleration up to relativistic velocities is performed far slower than the acceleration of a simple electron bunch with the same charge.

(c) While being accelerated the ring is polarized and ions are accelerated by the natural Coulomb forces. These forces are determined by the ring parameters and limited; hence the forces accelerating the ring must be limited too.

With those peculiarities being regarded accelerating elements of various types have been examined. As a principal accelerating element a h.f. cavity has been chosen.[20]

Due to the specific character of the interaction of the flying bunch with the accelerating system elements (small time of interaction) quasi-static calculation of the energy balance appeared to be not enough. The electrodynamic calculation of the cylindric cavity model shows that the main energetic losses of the bunch take place due to the excitation of TM waves. Estimates of the energy share of the external field stored in the interaction region (where the bunch while flying through takes back the energy), relating to the energy taken by the bunch in the ideal static field show that there is a possibility to use the cavity as an accelerating element for the ring with the number of electrons as high as 10^{14}.

However, considering acceleration peculiarities of the annular bunch and the necessity of the ring focusing in the acceleration process, it is possible to show that using single cavities in the accelerating system is of little effect.

To increase the acceleration efficiency a system using effects of falling and rising longitudinal magnetic fields together with the system of single cavities has been examined. As is known, this system has the following structure.[21] In the region between the cavities the longitudinal field decreases according to a linear law and the ring inside it is accelerated due to the energy of the rotational movement. Inside a cavity the longitudinal magnetic field increases so that energy is transferred basically into rotational movement of the particles, and only part of the energy (which corresponds to the tolerable acceleration) contributes to movement directly along the axis; longitudinal magnetic field at the cavity exits is the same. Hence the azimuthal impulse is the same.

Calculations show that this system proves to be highly advantageous as compared with the system of single cavities. It is evident that the last part of the accelerator (from half to two-thirds) may not contain cavities at all, but just use the features of the falling magnetic field.

This choice of the accelerating system is based on calculations of the interaction between the bunch and a single accelerating element, which is not quite correct. The accelerating system naturally provides the appearance of the space inhomogeneities in the canal. Hence, flying along the canal a relativistic bunch with a large charge loses a part of its energy from coherent radiation while passing through the space inhomogeneities, i.e., from transition and Cherenkov radiation. The most important thing here is the dependence of this radiation power on the bunch energy. The exact solution of such a problem for a given periodical system is of great mathematical difficulty, but the character of the dependence can be understood while examining various models. Dependence of the radiation power on the bunch energy appears to be significantly different for the case of a single obstacle and for the periodical structure. For the single obstacle full losses of the bunch energy rise proportionally to γ of the bunch, as the interaction time grows with γ. For periodically repeating obstacles the whole picture changes. It can be understood quite easily in the following interpretation. While passing obstacles the self field of the bunch is substantially changing, which explains the radiation. Then during the formation period (it is proportional to γ) the self field is restored. If the period of the structure is larger than that of the formation, the interaction with the structure is just equal to the sum of interactions with the single obstacles, so radiation grows with γ. If the field of the bunch is not formed on the period, the bunch does not feel practically the next obstacle and its radiation does not grow with γ. We come to this consideration after having scrutinized results of various model problems. One can get exact radiation magnitude in such a structure either after the exact problem with regard to the bunch acceleration has been solved, or experimentally. Those are the fundamental physical premises which ground the creation of the accelerating section. When designing an ultra-high-energy accelerator account must be taken of the fact that the biggest part of its cost is due to the accelerating section, which is why the choice of the system should be approached particularly carefully. The analysis shows that to use superconducting cavities is most profitable. But creation of such a section required examination of a number of new questions, among them possibilities of using superconductors in the magnetic fields. These experiments have been started, and the first results obtained[22] assure us of the possibilities of creating the superconducting cavity system. So by the theoretical and experimental work of the Dubna team is proved the possibility of creating the accelerator, in which effective accelerating fields acting on ions can reach 10^7 V/cm, which is far greater than the effective fields in now operating accelerators. Creation of accelerators for ultra-high energies is the main direction in Dubna researches today. But detailed investigations of this method show a number of other directions also important for modern nuclear physics. First of all is an accelerator for multi-charged ions. As the calculations show[12] it is quite simple to accelerate any ions, even uranium, with high enough intensity (10^{13} sec^{-1}). Examination of different ways of accelerating heavy elements shows that quite a few of them can be used in researches concerning distant transuranium elements. One of these methods is the collective effect of acceleration.

Creation of accelerators for not high energies (up to 1 GeV) with high intensity of particles is of significant value in medicine, radiochemistry, etc. Those energies can be obtained in the collective accelerators without special accelerating systems using only acceleration in the decreasing field. It gives the possibility to increase significantly the repetition rates of the bunches. If we consider technical possibilities now existing, we can speak of intensity of 10^{15} per second. This intensity is equal to that of meson facilities. Even the short observation shows that the collective method of acceleration opens new perspectives in the development of different areas of nuclear physics. However, as we think, the main perspectives of this method are in creating extremely effective accelerators for ultra-high energies. In this case quite a special place is devoted to the relativistic self-focusing ring. G. I. Budker proved that in the intense electron beam, compensated with the ions so that $N_i = N_e/\gamma^2$, due to magnetic compression the cross section of the beam decreases because of the energy losses of the radiation due to transverse motion of the particles. This decrease of the cross section continues until the collisions of electrons with ions start acting and the ring comes into the stationary state. For the ring with a number of particles, obtained in the collective accelerator, the stationary state comes at the dimensions of the transverse cross section equal to 10^{-4} cm. Then the effective intensity of the field acting on the ion reaches 10^9 V/cm. To use all the possibilities of the ring in the accelerator for ultra-high energies it is necessary to have the intensity of the external field accelerating the ring equal to 10^7 V/cm. At present it can be fulfilled in two ways: to use either impulse lines with persistence of the impulse less than one nanosecond, or impact acceleration, in which the energy transfer is proportional to γ^2. Hence, these are real possibilities of creating an accelerator providing quite a fantastic gain of particle energy, 100 GeV per meter of the accelerator's length.

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