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Linear Accelerator on a Traveling Wave with a Coherence Front Shift with a Potential Rate of Up To 1 - 10 Gev/M

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Annotation

Based on a new approach to the implementation of linear accelerators based on general physical principles, a new type of linear accelerator is considered. The paper shows the fundamental possibility of creating linear accelerators with an acceleration rate of charged particles up to 10-100 GeV/m and higher, and with a higher acceleration rate when switching to millimeter-wave waves. In a full-fledged version of a linear accelerator in the form of a sequential series of sections, energy in E = 3 TeV is achievable on an accelerator with a length of only 300 m. In this case, a collider on counter $e^- - e^-$, or $e^+ - e^-$ beams is of interest.

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Introduction

Currently, the development of accelerator technology for high-energy physics has led to the need to create compact accelerators with a high rate of particle acceleration, in particular, to study the wave properties of neutrinos, which could be associated with additional exotic dimensions that expand the geometry of visible $D=(3_s+1_T)$-dimensional space-time, with the Lorentz symmetry group SO (3,1) and the 4-dimensional translation group P^4.

Further progress in the development of our "standard" concepts will certainly be associated with penetration into the depths of matter at distances $r \leq 10^{-16} \div 10^{-21}$ cm. It is expected that this progress will be achieved to a large extent with the commissioning of a new generation of accelerators, which can be divided into two main classes according to the operating method and the range of tasks covered.

The first class includes ultrahigh-energy collider accelerators ($pp, p\bar{p}, ep, e^+e^-$), on which it will be possible to conduct a direct thorough experimental study in the field of energies 1-10 *TeV* ($r \leq 10^{-16} \div 10^{-18}$ cm).

The second class consists of accelerators with super-intense beams operating in the fixed target mode. This refers to the so-called factories of π^-, K^-, and D^-mesons and intense beams of *ν*, where it will be possible to search for rare processes with partial widths of $B \leq 10^{-10} \div 10^{-16}$. This may be due to the virtual effects of the "new physics" at distances $r \leq 10^{-17}$ -10^{-20} cm.

Accelerator on a Traveling Wave with a Shift in The Coherence Front of The Accelerating Field

Therefore, the question arises of creating more efficient linear accelerating structures [1-7]. First of all, this accelerating structure should be such that there are no accelerating electrodes on the axis of the structure, in the acceleration zone of charged particles, which will increase the rate of particle acceleration in the accelerator. During the acceleration process, simultaneous focusing of the accelerated beam must be ensured.

There is a known method of accelerating charged particles in linear resonant accelerators [8]. Charged particles are accelerated between accelerating electrodes in a structure with span tubes and with a resonantly excited standing wave. The level of accelerator parameters achieved: proton energy of 600-800 MeV, pulse current value of 20-50 mA, average current value of about one milliampere. For example, the length of the LAMPF linear accelerator is about 800 m and the acceleration rate is up to 1 MeV/m. The disadvantages of the method and device are the limitation in the rate of particle acceleration due to breakdowns $U_{pr} < 10^6$ V/cm. between the electrodes.

The acceleration of particles in linear accelerators on a straight traveling wave is known [9]. In this case, the long waveguide is loaded with disks, which are positioned so that the velocity of the accelerated particles is optimal during acceleration. When the electrons accelerate, the acceleration rate reaches 10 MeV/m. There is also a known acceleration method and a linear accelerator on a traveling reverse wave [10]. In this case, the microwave energy flow is directed towards the injected particles and the decelerating system is made in the form of counter pins in the waveguide, the pitch of which is selected to increase from the input injection end to the output end, in accordance with the change in the velocity of the equilibrium particle. The acceleration rate reaches 10 MeV/m.

The Main Provisions

A prerequisite for creating a new type of accelerator [11] is that with the radial convergence of the initial accelerating driving field to its axial region, and the absence of structural elements on the beam axis in it, this magnitude of the traveling accelerating field can be increased by $R/\lambda \sim 10^{2\text{-}3}$ times – up to $10^{8\text{-}9}$ V/cm. And accordingly, the acceleration rate can reach 10^9 eV/cm. Where R is the radius at which the source forming the radially converging wave is located, and λ is the length of this wave.

The base is a modified accelerating metal plate lens. A metal-plate lens is a series of plates parallel to the vector of the electric field strength of the incoming wave. If an electromagnetic wave falls on its plates, the vector E of which is parallel to the plane of the plate, then a wave is formed between them, the phase velocity of which is: $V_f = \dfrac{c}{\sqrt{1-\left(\dfrac{\lambda}{2a}\right)^2}}$. (1)

where a is the distance between the plates selected from the propagation condition of an E_{10} type wave ($\lambda/2 < a < \lambda$), λ is the wavelength in free space. The phase velocity of the V_f wave in a metal-plate lens is greater than the speed of light.

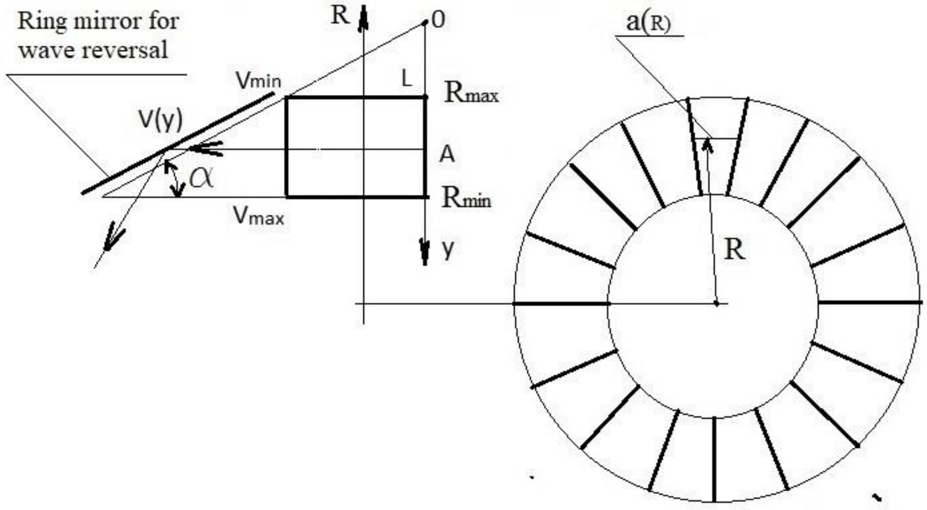

Figure 1: Characteristics of the Coherence front Shaper plates

The space between the plates can be considered as flat waveguides, the size of the walls of which (height) is significantly greater than the distance between the plates a.

These waveguides have an effective refractive index

$$n = \frac{c}{V_{\phi}} = \sqrt{1-\left(\frac{\lambda}{2a}\right)^2} < 1 \qquad (2)$$

The *E* wave of the main type propagates in them. The forming radial metal-plate lens is made axisymmetric, and the edges of the plates at the entrance and exit of the lens are purely radial and perpendicular to the direction of beam movement, and the distance between the plates increases with the radius in the direction perpendicular to the axis of the accelerator.

Since the rays enter and exit perpendicular to the edges of the plates at the input and output of the coherence front shaper, the wave rays move axially through the lens, parallel to the axis of the accelerator without changing the direction of their movement.

However, as a result of the axial symmetry, the distance between the plates on the outer part of the bell and on the inner part of the bell, are different, and therefore the wave speeds in these areas are different.

At the entrance to the lens, both the vector E of the wave and the coherence front of the wave are perpendicular to the beam of the wave, and at the exit of the lens, the coherence front is inclined to the direction of movement of the beam of the wave.

This creates opportunities for a new approach to creating accelerator technology.

A radially converging wave, reflected from an annular mirror, is directed towards the axis of the accelerator with an inclination against the direction of motion of the accelerated particles, as in an accelerator based on a reverse accelerating traveling wave.

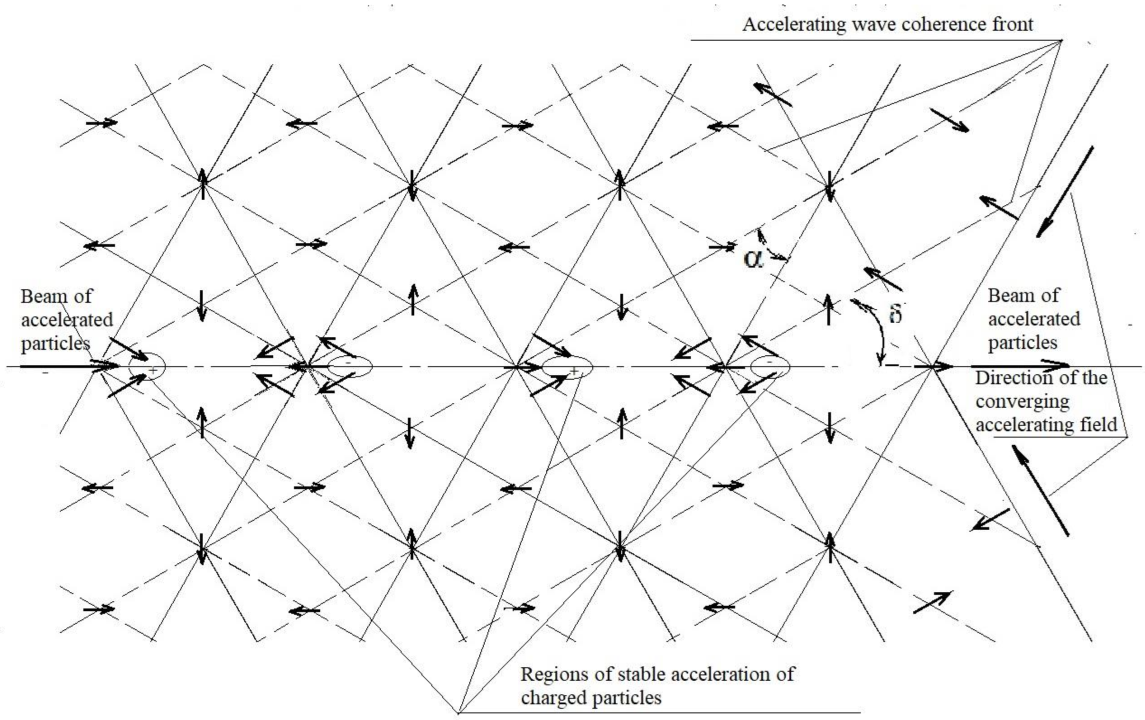

Figure 2: Formation of the process of acceleration and focusing on the reverse wave on a virtual rotated coherent front

It is necessary that the coherence front of the accelerating wave with the conical surface of the coherence front of the wave moves in such a way that the intersection point of the conical coherence front of the accelerating wave with the axis of the accelerating structure is greater than or equal to the velocity of the accelerated particles. It is enough $0{,}5 \le a/\lambda \le 1$. for a wave to exist, but let's take a more rigid framework. In order for only this wave to exist, the distance between the plates must be within the limits $0{,}58 \le a/\lambda \le 0{,}7$.

Let's take these thresholds: $1{,}43 \le \lambda/a \le 1{,}72$.

Because with a small plate thickness, the distance between them is $a = 2\pi \cdot R/N$, where, R is the radius, and N is the number of plates in the coherence edge shaper. From here, for a given range, we can find the ratio of the radii of the upper and lower edges of the plates of the coherence front shaper $R_{max} / R_{min} = 1{,}2$, and the width of this plate will be $A = 0{,}2 \cdot R_{min}$. And the range of change of phase velocities will be:

$$V_{min} = 1.42 \cdot c \leq \frac{c}{\sqrt{1-\left(\frac{\lambda}{2a}\right)^2}} \leq c \cdot 1.96 = V_{max} \quad . \tag{3}$$

The phase velocity of a wave in it can be almost 2 times the speed of light.
This leads to the fact that both the vector E of the wave and the elements of the coherence front lying closer to the axis of the accelerator are ahead of the external elements of the front, which forms the slope (taper) of the coherence front of the wave coming out of such a device.

At the same time, at the output of the coherence front shaper device, the slope of the coherence front can be represented as: $tg\alpha = \frac{A}{L} \frac{V_{min}}{V_{max} - V_{min}}$ (4)

Assume that the slope of the coherence front to the direction of the wave movement after it is $\alpha = 30^0$.Hence, the length of the coherence front shaper plate will be:

$$L = \frac{A}{tg\alpha} \frac{V_{min}}{V_{max} - V_{min}} = 0.2 \cdot \frac{R_{min}}{0.577} \cdot \frac{1.42}{1.96 - 1.42} \approx 0.911 \cdot R_{min} \, . \tag{5}$$

At the exit from the lens, the vector E of the wave remains perpendicular to the wave beam, but at the same time, the coherence front of the wave at the exit from the lens is no longer perpendicular to the direction of wave motion. In this case, the focusing component of the traveling wave has some redundancy and is of interest for accelerating high-current beams, assuming that this slope is $\alpha = 40^0$, we obtain that:

$$L = \frac{A}{tg\alpha} \frac{V_{min}}{V_{max} - V_{min}} = 0{,}2 \cdot \frac{R_{min}}{0.84} \cdot \frac{1.42}{1.96 - 1.42} \approx 0.63 \cdot R_{min} \, . \tag{6}$$

So, they implement a method for accelerating charged particles by an electric field wave with a coherence front, such that a combination of wave elements with the same phases forms an axisymmetric surface characterized by the fact that a wave is formed, the coherence front of which forms a conical surface. And they direct it to the accelerator axis so that the intersection point of the conical coherence front of the accelerating wave with the axis of the accelerating structure is close to the velocity of the accelerated particles.

In this case, it is necessary that: in the secant plane running through the accelerator axis, the path traversed by the accelerated beam along the accelerator axis during the period of field change and the path traversed by the accelerating field wave along the direction of its movement to the accelerator axis during the period of field change are equal.

They form a triangle together with the cross-section line of the accelerating field wave by the coherence front of this field. In this case, the accelerating wave must be reversed, i.e. the angle between the direction of the radially converging wave front of the accelerating field and the direction of acceleration is greater than 90^0.

When the path traversed by the accelerated beam along the axis of the accelerator and the path traversed by the wave of the accelerating field along the direction of its movement to the axis of the accelerator during the period of field change are equal and form an isosceles triangle together with the plane of coherence of this field, an axial traveling accelerating wave is formed, which accelerates the charged particles. Moreover, if the accelerating wave is reversed, that is, the angle between the direction of the radially converging wave front of the accelerating field and the direction of acceleration of charged particles is greater than 90^0, then the radial component of the accelerating field is directed towards the axis of the accelerator and therefore the bunch of accelerated particles is simultaneously accelerated and focused at the axis of the accelerator.

And also, changing the inclination of the accelerating field wave to the accelerator axis changes the force focusing the beam and, accordingly, the current at the accelerator output. Since the wave of the accelerating field is alternating, simultaneous acceleration of both positively charged particles and negatively charged particles in neighboring half-cycles of the accelerating wave is possible in an accelerator on a traveling wave. It is also possible to achieve the effect of collective acceleration of a group of positively charged particles inside a neighboring negatively charged electron bunch by its collective field.

It is important that the coherence front of the accelerating wave is conical and moves so that the virtual intersection point of the conical coherence front of the accelerating wave with the axis of the accelerating structure is equal to the velocity of the accelerated particles. And the speed of movement of this point and therefore the speed of the accelerated particles should be:

$\beta_q = \frac{V_q}{c} = \frac{\sin\alpha}{\sin\delta}$. And when, for example, α = 30^0 δ = 30^0, then in the process of acceleration: $\beta_q = \frac{V_q}{c} \to 1$ and $V_q \to c$, $\gamma = \frac{1}{\sqrt{1-\beta^2}} >> 1$. (7)

In addition, by choosing the input phase of the accelerated particles, it is possible to select the conditions for optimal autophasing of the beam during acceleration. Such an area is located on the growing (initial) section of each virtual accelerating cell and moves along with the accelerated particles.

The proposed linear accelerator of charged particles by an electric field wave, containing a field source, a field input device, an irradiator, and a source of accelerated particles, is characterized in that it additionally contains an accelerating wave generation device with a coherence front rotated relative to the direction of wave motion, which contains an annular emitter in the form of an annular cylindrical resonator, an annular horn antenna (bell), a corrective lens forming a metal-plate lens and a device for rotating an annular directional wave (see FIG. 3).

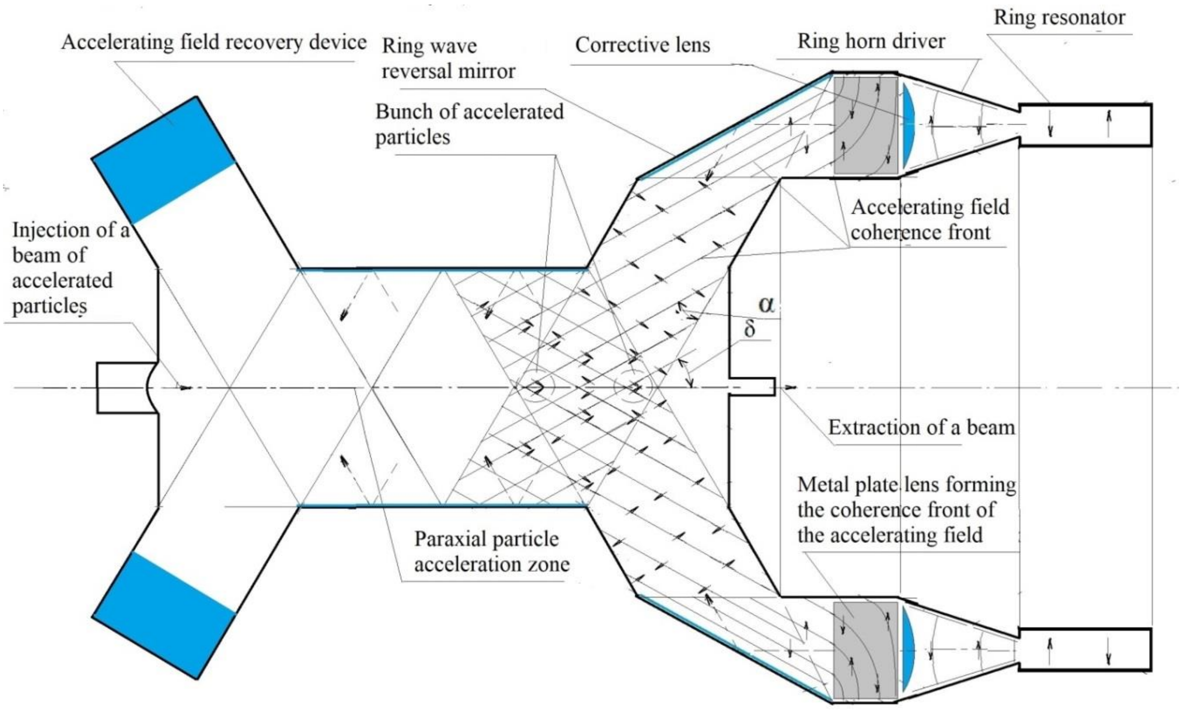

Figure 3: Accelerator with a coherence shift of the accelerating field (schematically).

For this purpose, in the proposed accelerator design, in the axial region, in the section of the plane passing along the accelerator axis, the intersection points of the opposite converging conical coherence fronts of the accelerating electromagnetic wave is virtual (similar to the virtual intersection point of the scissors blades).

In this case, the direction of the electric field vector at the coherence front of the wave is such that a region of steady acceleration of a cloud of charged particles is formed with their auto-phasing along the accelerator axis and focusing across and to the axis.

Let us consider the process of forming a radially directed accelerating wave, with a shift in the coherence front of the accelerating field and with a virtual acceleration cell. As a field source, we will use an annular irradiator in the form of an annular cylindrical resonator. The width of the annular waveguide is a multiple and comparable to the wavelength of the accelerator in it, and ranges from units of millimeters to centimeters. Let's take an accelerating metal-plate lens with an annular radiating opening in the form of a horn antenna with an *E*–planar sectoral horn, enclosed in a ring with the width of the antenna mouth at the outlet - H. This is due to the fact that the radiation pattern of the resonator output slit without a horn is extremely wide (up to 50^0). The horn allows you to form a narrow directional pattern of the wave formed by the resonator with a width of $\theta_{P/2}$.

$2\cdot\theta_{P/2}=51^0\,\dfrac{\lambda}{H}$, where λ is the wavelength, *H*=*A* is the width of the mouthpiece at its outlet. At the same time, the optimal maximum horn length is: $R_E=\dfrac{H^2}{2\lambda}$ (8)

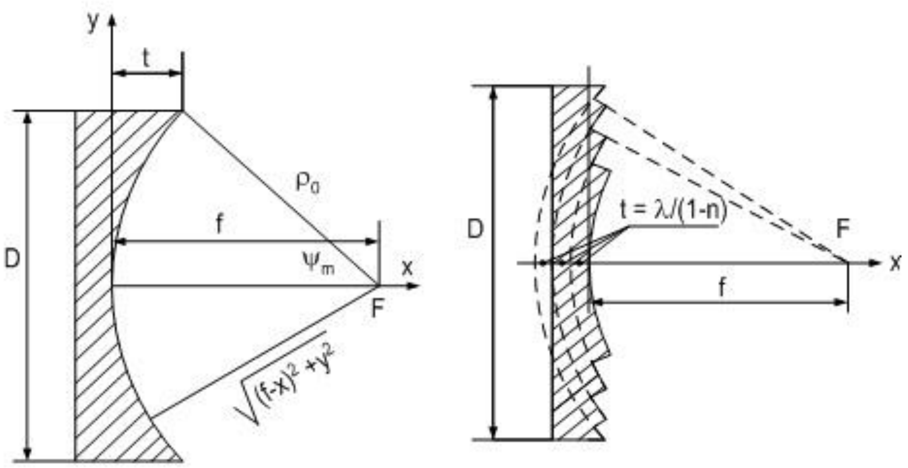

Figure 4: An example of the entrance section of a metal plate corrective lens

To form a purely radial (relative to the axis of the accelerator) and flat input coherence front of the generated wave, a dielectric or metal-plate, annular corrective lens is placed at the outlet of the irradiator socket. A metal-plate, annular corrective lens forming a radially polarized input annular wave can be made together with a forming metal-plate lens forming a rotated coherent accelerating wave front. In a dielectric correction lens, the speed of the wave is less than the speed of light: $V = \frac{c}{\sqrt{\varepsilon}}$, where ε is the dielectric constant of the lens material, which, for example, is ε ≈ 4.0 for viniplast. Therefore, the correcting dielectric lens must be convex, and its shape at the entrance is an elliptical cylinder.

Then an annular wave rotation device is placed - an annular guiding conical mirror that unfolds the annular directional accelerator wave with an inclined coherence front formed at an angle δ to the accelerator axis and at the same time against the direction of motion of the accelerated beam.

As a result, a *virtual* intersection point of converging coherence fronts of the accelerating electromagnetic wave appears in the axial region of the accelerator in the form of a *virtual* "bulldozer bucket". In this case, a region of steady acceleration of the charged particle beam is formed with their spontaneous phase locking along the accelerator axis and focusing across and to the axis.

It is essential that the direction of the accelerating field in sequentially alternating virtual cone coherent fronts has an alternating character. Therefore, simultaneous acceleration of particles of different signs in bunches following one another is possible. In general, the beam is electroneutral, which may be the basis for using the device as an electric propulsion system for space.

Moreover, since this value is comparable to the strength of the longitudinal accelerating field, the value of the accelerated particle current can be at least 10^2-10^3 times greater than the current accelerated by conventional linear accelerators. Then, it is necessary to multiply the acceleration process. Therefore, the next element of the accelerator is the main cylindrical acceleration region of charged particles. Its radius R_y must be a multiple of the value $\lambda \cdot cos30^0$ and at the same time must be greater than the value $H/cos30^0$, and the length is a multiple of the radius R_y.

The beam acceleration process is also underway in this area. An increase in the length of the cylindrical part makes it possible to increase the total energy of the accelerated beam.

When accelerating heavy charged particles, the radius of the cylindrical part can be variable, and the accelerator is partitioned in a chain of accelerating sections with different magnitudes $\beta_q = \frac{V_q}{c} = \frac{\sin\alpha}{\sin\delta}$.

At the entrance (exit) of the cylindrical zone of the accelerator, there must be an induction or capacitive energy recovery device for the accelerating wave, which can be returned to the accelerator operation cycle.

Role of the Magnetic Insulation Effect

It is extremely important that the accelerator surfaces are mainly cylindrical in shape, and in such crossed *E-H* fields, it is possible to protect the surfaces from breakdowns by magnetic insulation of the electrodes from breakdowns. The breakdown electron, having left the surface by the action of a magnetic field, returns back. Thus, already in the initial annular resonator with magnetic insulation protection of the resonator – in the source of an accelerating traveling wave with a magnitude of, it is permissible to obtain a field strength of $E \approx 2x10^7$ (In /cm) < H‖=10T. Therefore, in such an accelerator it is possible to have a Source = $2x10^7$ (V/cm).

Evaluating Accelerator Options

At $R_{min} \approx 1m$ and $\lambda \approx 0.5 \div 1\ cm$, the magnitude of the traveling accelerating field can reach $R/\lambda \sim 10^{2\text{-}3}$ times - up to $E_{usk} = E_{source} \cdot R/\lambda = 10^{10\text{-}13}\ V/m$ and, accordingly, the acceleration rate can reach $10^{10\text{-}13}\ eV/m$. Where R is the radius at which the source is located, forming a radially converging wave, and λ is the length of this wave.

In this case, the coherence front former plates have a size of 20x63 cm.

That is, it is possible to create an accelerator with a rate of up to 10-100 GeV/m, and with the transition to millimeter waves, with a higher acceleration rate. And over a length of the accelerating section of about 20 cm, it can be accelerated to 2-20 GeV.

Let us estimate the current of particles accelerated by the accelerator.

We assume that the microbunch of a beam accelerated over a length *λ* has a diameter of *0.2λ,* and the force of its Coulomb repulsion is compensated by the focusing field of the traveling accelerating wave $E_{fok} = 0.1 \cdot E_{source} \cdot R/\lambda = 10^9$ *V/m*, as a result the microbunch contains 10^{12} charged particles and a charge $q_b = 4 \cdot 10^{-7}$ coulomb.

This is equivalent to the accelerated current $I_u = c \cdot q_b/\lambda = 1 \cdot 10^4$A and the flux $\Phi_u = 8 \cdot 10^{22} s^{-1}$.

The actual intensity of the beam of charged particles generated by such an accelerator is determined by the power of its energy supply system.

Tricollider

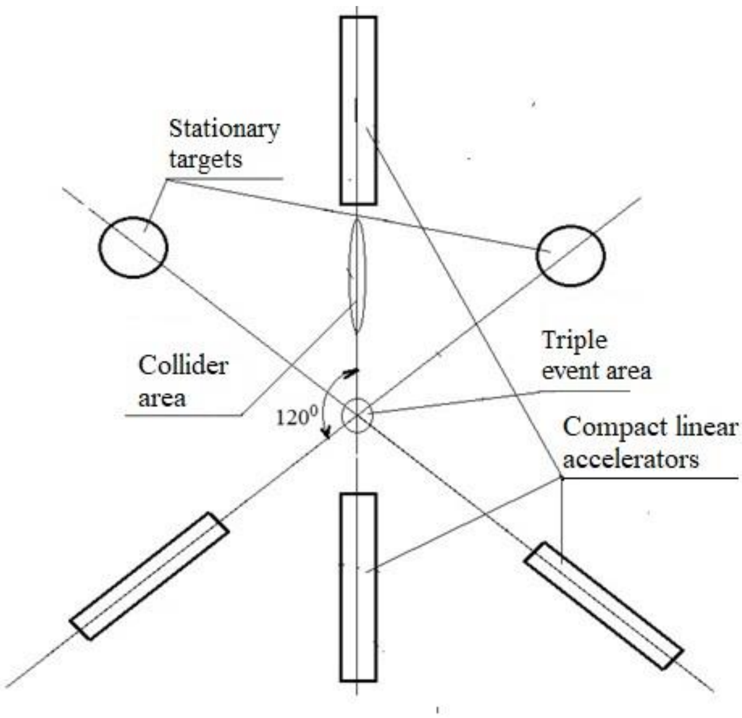

Figure: 5 Tricollider

The compactness of the proposed accelerator poses the task of creating a new accelerator complex based on a new type of linear accelerators according to the tricollider scheme,

$$S_3 = 9 \cdot E^2 > 4 \cdot E^2 = S_2, \qquad (9)$$

which allows you to increase the threshold of energies and masses of the resulting secondary particles (This is the idea of G.G. Volkov).

Conclusions

So, the work shows the fundamental possibility of creating linear accelerators with an acceleration rate of charged particles up to 10-100 GeV/m and higher, and when moving to millimeter waves, with a higher acceleration rate.

Even in a minimal configuration without a cylindrical region of acceleration of charged particles with a length of 2 m of the entire structure, a flux $\Phi_u = 8 \cdot 10^{22}\ s^{-1}$ and a proton beam energy of *2 GeV*, it can already be of interest as a high-current source of μ, K and ν. What is also interesting is how a compact space accelerator of charged beams is used.

In a full-fledged version of a linear accelerator in the form of a sequential series of sections, an energy of $E = 3\ TeV$ is achievable on an accelerator only 300 m long. In this case, a collider using colliding e^- - e^-, or e^+ - e^- beams is of interest.

The method of acceleration on a backward traveling wave with a shift of the coherence front of the accelerating field allows:

1. Solve the problem of simultaneous longitudinal and transverse stability of accelerated charged particles.
2. Carry out simultaneous acceleration of particles of opposite signs in adjacent bunches of the accelerated beam.
3. Effectively capture a beam of charged particles injected into the accelerator into a stable acceleration mode.
4. Increase the frequency of the accelerating field by 100-1000 times and carry out acceleration in the centimeter and millimeter wavelength range.
5. Reduce the longitudinal dimensions of the accelerating structures by two orders of magnitude.
6. Increase the intensity of the accelerated beam current to two or more orders of magnitude.
7. It becomes possible to create compact tricolliders.

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