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DEVELOPMENT AND PROSPECTS FOR THE APPLICATION OF MESON FACTORIES

Invited Paper

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(Presented by V.P.Dmitrievsky)

I.Introduction

In 1960 the development of the 700 MeV proton accelerator design (a meson factory) was started at the Laboratory of Nuclear Problems (Dubna). The basic features of the design[1] have been reported at the International Conference on High Energy Accelerators in 1963 at Dubna. In the course of designing which is still going on at present there were no considerable changes of the design. Some details related to the central optics of the accelerator, to correction coils placed at the spiral shims of the pole faces as well as to proposals on the development of the beam extraction system have been reported in refs.[2,3,4]

However, on the whole the design of the relativistic cyclotron (RC) at Dubna as well as other similar meson factories such as the Mc^2, the H^- cyclotron, the[5,6,7] 500 MeV cyclotron in Zurich are progressing at a rate far from being relativistic. This can be explained mainly by the fact that the emphasis of nuclear investigations shifted to the 10 GeV region and higher whereas low energy physics is slowly moving along the experimental region below 100 MeV and has not approached yet the region of meson energies of protons (500-800 MeV).

Some "vacuum" in the progress of this energy range was due to the absence of common opinion on the optimal type of the meson factory. The existence of five, equivalent, as it might seem, designs of meson factories in the USA (the Mc^2, the H^- linear accelerators of the Yale University and the Los-Alamos Laboratory, SOC) essentially affected the solution of problems on meson factory construction. The discussion of these problems is still underway and appears to be continued at the present conference.

2. The Proposed Utilization of the Meson Factory

The production of secondary particle beams is proposed for experiments at a distance of 15 m from the target in the designed relativistic cyclotron.

Table 1

Part.	Energy (MeV)	Intensity (sec^{-1})
p	700	$2.5.10^{15}$(the extracted beam)
π^+	300	1.10^{10} ($S=200\ cm^2$)
π^-	300	6.10^8 ($S=200\ cm^2$)
μ^+	150	1.10^8 ($S=200\ cm^2$)
μ^-	150	2.10^7 ($S=200\ cm^2$)
$\hat{p}$	660	4.10^{10} ($S= 20\ cm^2$)
n	630	1.10^8 ($S= 20\ cm^2$)
ν_μ	30	5.10^7 $1/cm^2.sec$

In our opinion, meson factories will make a new epoch in experimental investigations with high energy particles.

First of all, the application of such accelerators will permit to solve many basic heretofore uncleared problems of fundamental particle physics and the atomic nucleus as well as to outline new ways of developing this branch of sciencence in the pre-GeV energy region. Here are some of them.

As far as weak interactions are concerned the use of muon and pion beams of high intensity provides a possibility of checking up the universal weak interaction theory (experiments both on ordinary and radiative muon capture in gaseous hydrogen, the detailed study of the radiative decay and the pion-beta decay,etc.) to check up the validity of the CPT-theorem and to clear out the possible violations of the C,P and T interaction invariance. Experiments with monochromatic neutrinos will be possible in new conditions which will permit to more strictly determine the muon neutrino mass, its helicity, etc. The rare processes of single hyperon production

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($p+p \rightarrow \Sigma + p$, $p+n \rightarrow \Lambda + p$) in nucleon-nucleon collisions due to weak interaction will be investigated).

As far as strong interactions are concerned, the problems of pion-pion interaction can be solved, the T-invariance can be checked up, the validity of SU_6 and higher symmetries can be cleared out. The atomic nucleus structure, various nuclear reactions induced by pions can be studied. The properties and quantum characteristics of the isotopes of atomic nuclei far remoted from the stability region by neutron defficiency can be discovered and investigated.

Undoubtedly, a new powerful pion source and high energy nucleons will permit to increase by an order of magnitude the accuracy of many important earlier performed investigations and thus to considerably raise their scientific value.

Strong current accelerators open new wide vistas for investigations in other branches of science too: radiochemistry, solid state physics, chemical kinetics, byology, radiation therapy (even the treatment of cancer with pion beams) as well as the solution of problems on radiation safety of long-term space flights of the man, etc.

The construction and utilization of meson factories will be a very important step in the course of developing in future the accelerators of hundreds of times still more powerful. The latter having neutron breeder reactors will be large power systems of practical value (production of nuclear fuel with simultaneous releasing some amount of power to the supply system). Such systems may also be needed if it is necessary to obtain neutron fluxes of high density[8] (about $10^{16} - 10^{17}$ n/cm^{2}sec) the production of which with conventional nuclear reactors may turn out practically impossible.

3. Development of Theory

a) Particle Dynamics

After the linear theory of stability in spiral ridge accelerators had been investigated and a study was made of the nonlinear resonance such as

$$qQ_r \pm pQ_z = N \qquad , \qquad (1)$$

where N is the periodicity of the magnetic field structure, p and q are integral numbers, nonlinear effects in the regions between resonance values of natural frequency oscillations were studied.

By using the JINR electronic computer the numerical solutions of the set of equations were analysed

$$\begin{aligned} r'' - \frac{2r'^2}{r} - r &= -\frac{e}{pc}\left(1+\frac{r'^2}{r^2}+\frac{z'^2}{r^2}\right)^{1/2}\Big[(r^2+r'^2)H_z - \\ &\quad - z'r'H_r - z'rH_\varphi\Big], \\ z'' - \frac{2r'z'}{r} &= \frac{e}{pc}\left(1+\frac{r'^2}{r^2}+\frac{z'^2}{r^2}\right)^{1/2}\Big[(r^2+z'^2)H_r - \\ &\quad - z'r'H_z - r'rH_\varphi\Big] \end{aligned} \qquad (2)$$

for the magnetic field of the form

$$H_z(r,\varphi,0) = H(r)\{1+\varepsilon(r)\sin[\alpha(r)-N\varphi]\} \qquad (3)$$

with p = const.

The investigations showed that along with the change of natural frequency oscillations[9] which is due to the nonlinear terms of equation (2) there takes place the variation of free oscillation frequency due mainly to the dependence of the magnetic filed along the axis Z. The scale of this effect for initial amplitudes close to $1/2(d\alpha/dr)^{-1}$ turns out to be sufficiently large and cannot be compensated by the effect of damped oscillations which is defined by the increase of the average magnetic field along the radius. For the beam whose size is not larger than 1.5 cm in the axial direction these effects can be neglected.

b) Effects of the Proper Field Beam

Since the tolerance of the Z-component of the magnetic field strength is 10^{-4} in relativistic cyclotrons, it is interesting to evaluate the mean intensity of the magnetic field produced by the beam (J) incident on the target. It can be shown that the field is described by the expression

$$\overline{H}_z = \frac{J}{2\pi r_\infty} \cdot \frac{E_0}{eV} \cdot I(\beta_0),$$

where

$$I(\beta_0) = \int_{\beta_H}^{\beta_K} \frac{\beta}{(\beta+\beta_0)(1-\beta^2)^{3/2}}\left[K(k^2) + \frac{\beta+\beta_0}{\beta-\beta_0}E(k^2)\right]d\beta,$$

$$k^2 = \frac{4\beta\beta_0}{(\beta+\beta_0)^2}, \qquad r_\infty = \frac{c}{\omega_0},$$

eV is the average energy gain per turn, K, E are elliptical integrals of the I and II kinds.

The maximum value of the integral modulus in expression (4) for the accelerator of the energy $E = 2E_0$

$$|I(\beta_0)|_{max} = 26.5 \qquad (5)$$

that is

$$\overline{H}_{z\,max} = -4{,}2 \cdot \frac{J}{r_\infty} \cdot \frac{E_0}{eV} \qquad . \qquad (6)$$

If accelerator current is $J \leqslant 1$ mA, the mean value of the Z-component of the beam magnetic field does not affect

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isochronism.

Limitations introduced by the component of the electrical field (E_z) of the beam have been considered in [9,10,11]. Much less attention was paid to two other components of the magnetic field E_r, E_φ.

Suppose that for isochronous cyclotrons the value of the field component E_r is insufficient to cause noticeable change of the revolution period, i.e.

$$\frac{d\omega}{dE}=0 \quad . \tag{7}$$

This supposition is equivalent to the absence of the phase mixture of particles in the course of acceleration, i.e. there will be no effect of negative mass and the change of density can appear only due to the variation of particle radial step in the bunch. Since the electrical field of the accelerated bunch in the relativistic cyclotron is screened with closely place conducting surfaces of the dees and the chamber, the determination of the field components E_φ, E_z can be reduced to a two-dimensional problems. The bunch cross section along the axes φ (sometimes we use distance along other ones) is taken to be close to elliptical with half-axes l and b or to the rectangle having the sides $2l$, 2b. In this case the azimuth component of the electrical field of the bunch at rest E_x can be written in the form

$$\mathcal{E}_x=\frac{e}{2\pi\varepsilon_0}\left\{\int_{-l}^{l}\int_{\zeta_1(\xi)}^{\zeta_2(\xi)}\frac{\varkappa(\xi)(X-\xi)\,d\xi\,d\zeta}{(X-\xi)^2+\zeta^2}+\right.$$
$$\left.+2\sum_{K=1}^{\infty}(-1)^K\int_{-l}^{l}\int_{\zeta_1(\xi)}^{\zeta_2(\xi)}\frac{\varkappa(\xi)(X-\xi)\,d\xi\,d\zeta}{(X-\xi)^2+(2hK+\zeta)^2}\right\}, \tag{8}$$

where x is the number of particles in 1 cm^3 depending only on the direction along the azimuth (ξ); (ζ_2), (ζ_1) are the upper and lower limits of the bunch ($\zeta = \pm b$ for a rectangle, $\zeta=\pm b\sqrt{1-\xi^2/l^2}$ for an ellipse); 2h is the distance between conducting surfaces; ε_0 is the dielectric constant.

Table 2

Cross sect.	Ellipse			Rectangle
$h \diagdown l$	50	100	150	50 - 150
2	0.61	0.44	0.37	1.90
3	0.76	0.55	0.45	2.35
4	0.88	0.64	0.53	2.63
5	0.99	0.72	0.59	2.85

Table 2 enlists the value $D(h) = \mathcal{E}_x \Big/ \frac{e\varkappa}{\pi\varepsilon_0}$ for a rectangle and an ellipse having $x=l$, three values for l and b = 1 cm obtained by numerical integrating expression (8) on the electronic computer.

As is seen, with a rectangular section of the bunch the component $\mathcal{E}_x$ does not depend upon l within the given limits and exceeds the value $\mathcal{E}_x$ for an ellipse 3-4 times. Particle density in a bunch can be expressed through current on an immoveable target[8]. In this case the energy gain per revolution (eV) is determined by the external accelerating field and the longitudinal component of the bunch field. Taking this into account we obtain the expression for current

$$\frac{dJ}{dX}=\frac{ec\Delta_z}{2\pi\beta\gamma^3}\varkappa(\xi)\left\{\frac{eV_0}{E_0}\cos\frac{X}{R}+\right.$$
$$\left.+\frac{8\pi}{\gamma}R\cdot r_p\int_{-l}^{l}\varkappa(\xi)\cdot K(\xi,X)\,d\xi\right\}, \tag{9}$$

where R is the given radius of the beam cross section under study, r_p is the classical proton radius ($r_p=1.535.10^{-16}$cm) $K(\xi,X)$ is the main body of the equation determined by the bunch configuration, Δ_z is the axial size of the bunch, $\gamma=\frac{1}{\sqrt{1-\beta^2}}$.

Without solving equation (9), evaluate the effect of the longitudinal field considering that $S=2\pi R\mathcal{E}_x/V\ll1$. For small S one can consider the bunch uniformly charged under proper injection conditions. Then from (9) for a bunch edge at which the effect of the proper field decreases the energy gain per turn one can find, assuming $\frac{dJ}{dX}=\frac{J}{R\Delta_\varphi}$,

$$\left(\frac{eV}{E_0}\right)^2=\frac{16\pi^2 r_p\beta\gamma^2\mathcal{D}(h)}{ec\Delta_z\cdot S(1-S)}, \tag{10}$$

where Δ_φ is the azimuthal dimension of the bunch, D(h) is found from Table 2. Let us take, as an example, protons with $\gamma=1.75$, $\beta=0.82$, $\Delta_\varphi=0.5$, $\Delta=2$ cm, D=0,7 cm, S = 1/10, then we obtain

$$V = 9.2\sqrt{J}\quad , \tag{11}$$

where V(Mv), I(A). With $J=1$ mA the energy gain per turn is eV = 290 keV. It is natural that eq. (10) gives overestimated results of the required energy gain per revolution. As calculations on the effects of the beam space charge are approximate whereas resonance effects due to the presence of the chamber conducting walls (or electrodes) have not been checked up experimentally for configurations of the accelerated beam, the electron model of the relativistic cyc-

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lotron is assumed to start at the Laboratory of Nuclear Problems of the Joint Institute for Nuclear Research in 1967. With this model whose parameters are to reported at this conference it is planned to obtained charge densities to about 10^9 electron/cm^3, which will allow to investigate all effects due to the self-field of the beam including internal beam currents of tens of mA. (The general view of the set ups is shown in the Figure).

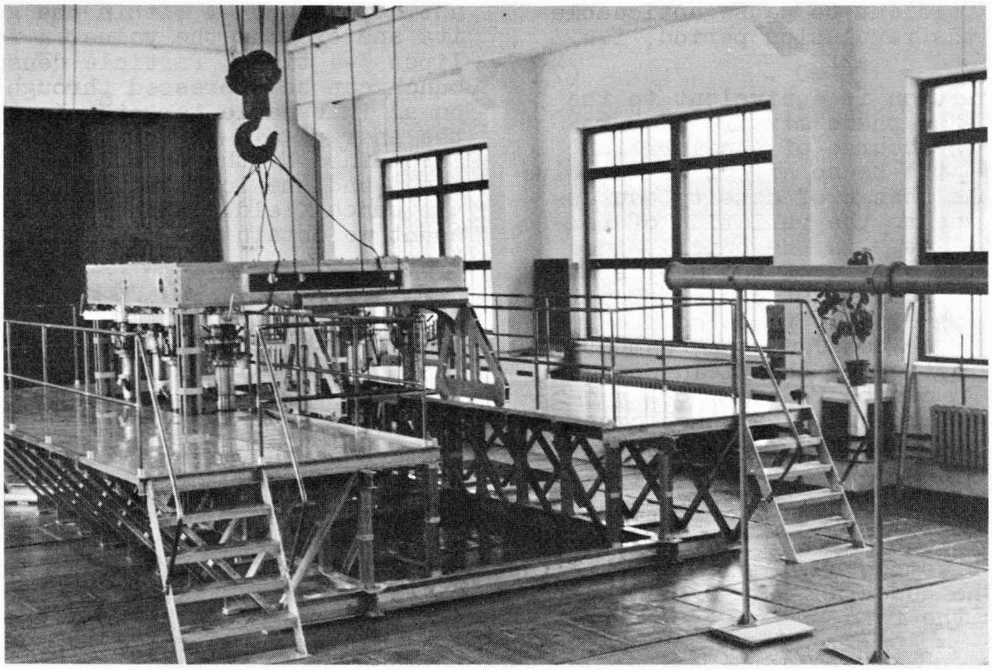

Fig.1. The general view of the analogue

4. Central Optics in the Relativistic Cyclotron

To insure the safe operation of the stabilization system of the flight phase[12] and to introduce the amplitude of free ion oscillations on which the efficiency of the extraction system and the phase washing-out of ion bunches greatly depend[13] it is necessary that in isochronous acceptance the ion phases should remain within $-15^\circ \leqslant \varphi \leqslant +15^\circ$ with respect to the maximum of accelerating voltage. Ions having negative phases undergo electrical defocusing and in order to avoid their loss at the beginning of motion it was decided to introduce the ion phase shift at the first half-turn at 20° in the positive direction according to the scheme proposed in ref.[14]. The introduced phase shift should be compensated at the moment of the beam entering the radius R_{is} corresponding to the start of isochronous acceleration. The detailed analysis of ion motion with the account of the real distribution of the magnetic and electrical fields has been made on the electronic computer[2]. The magnetic field was given by the expression $H(r)=H_o(1-hr^2)$, the electrical field configuration was found with an electrolitic tank. With $H_o=637000$ A/m, $h=8.10^{-2}(m^{-2})$ and the energy gain 400 keV/turn, $R_{is}=35$ cm is obtained at the tenth revolution, phases being distributed symmetrically with respect to the maximum of the accelerating voltage, whereas their region is narrowed approximately 2 times.

The central region for the 700 MeV RC was tested experimentally on the RC model of the scale 1:2[15]. As a result of the analysis of the obtained data the conclusion can be drawn that the experimentally chosen geometry of the central region has sufficienty well coincided with that calculated theoretically. Besides, as compared to the system without the central optical region the reduction of current at first revolutions became smaller, the stacking of orbit centres near the accelerator geometrical centre was improved, the beam vertical dimensions were reduced at small radii, the shape of current pulses of accelerated particles was improved.

5. Development of the Cyclotron Acceleration Method

As follows from the consideration of the effects of the space charge, in order to increase the limit intensity in a relativistic cyclotron, one has to increase free oscillation frequencies ($Q_{r,z}>1$) and the ion energy gain per turn.

The first and second conditions can be carried out in circular cyclotrons having external particle injection. Since the limit current of the internal beam with $Q_{r,z}>1$ is about hundreds mA, further rigidity of the system (as it takes place in SOC) is unnecessary. A still larger number of "independent" units of the magnetic system causes, as is known, the statistical growth of the free oscillation amplitude, a rigid tolerance for the corresponding harmonics in the field structure close to the value of natural oscillations frequencies being conserved. All the abovesaid proves the reasonability of considering the structure of the circular field having a small number of units and accelerating systems producing great ion energy gain per revolution.

The utilization of a linear accelerator as a meson factory is of special consideration.

There is no doubt that at the present-day level of development, it is difficult for a linear accelerator to compete with a circular machine at average currents close to 1 mA, which is due mainly to the pulse duty ratio determined by greater loss at a running meter of the linear accelerator cavity. However, in passing over to intensities of about 100 mA the beam power will considerably exceed this loss and the advantages of circular systems are quite evident in this case.

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Note: This paper was presented in Russian by V. P. Dmitrievsky, with translation by G. M. Volkoff.

DISCUSSION

LIVINGSTON: At the Dubna Conference in 1963 you had not fully decided what type of extraction system you would plan for the 700-MeV machine. Have you narrowed the choice, or made a decision on the type of extraction system?

DMITRIEVSKY: A preceeding paper, read by V. V. Kolga, dealt with this problem.