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PIONS AND MUONS ACCELERATION AT THE UNK–VLEPP FACILITY

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ABSTRACT

Considered is a scheme of acceleration in the VLEPP linacs of pions generated by 3 TeV proton beam extracted from the UNK. To match the time structure of extracted beam with that of linac the beam ejection is carried out one by one of 10^4 stored bunches with 100 Hz repetition rate by means of a special ejection system. In ejected bunch the longitudinal modulation of energy is produced with use of a regular element of linac structure. That permits by using a special magnetic tract to group the protons into very short sub-bunches corresponding to linac time structure. The pions are collected from target in tens GeV energy range in a wide relative interval $\Delta E/E \cong 1$. The lithium lens of 0.5 m focal distance is used to match the pion beam emitance with linac acceptance. Linac with its attendant focusing serves as well as a pion decay tract providing the produced muons with an acceleration up to the final energy.

The VLEPP linear accelerators [1] with their accelerating gradient ~ 100 MV/m being built in the same physical center, where the 3 TeV proton storage ring UNK [2] is under construction, will open the unique possibility to obtain the accelerated beams of pions and muons in TeV's energy range. High accelerating rate here is of the principal importance to prevent a significant part of pions from decay during the acceleration. High energy of extracted from the UNK proton beam will provide with a high efficiency for pion production.

To match the time structure of extracted proton beam with the VLEPP linacs time structure the beam ejection is to be carried out one by one of ~ 10^4 stored bunches by means of a special ejection system [3], operating at 100 Hz repetition frequency, that of the VLEPP operation. Ejected bunch is of ~ 10 cm r.m.s. length. To be matched with 2 cm wave length of the linacs it is to pass through a so called buncher consisting of a 30 GeV regular linac unit and a special bending channel. Correlation of energy gain in linac unit with longitudinal coordinate of particle results in a grouping of protons in the channel into short subbunches, distanced by 2 cm. Such grouped the proton beam is used for pion production.

Spectrum of pions, produced by high energy proton, in the central part of collision is described in accordance with Landau hydrodynamic model by the gaussian distribution of particle rapidity y about the CMS rapidity y_0 with a width, defined through the CMS Lorentz-factor logarithm $L = \ln\gamma$ [4, 5, 6c, 6d]:

$$dN_\pi/dy = \frac{\langle n_\pi^\pm\rangle}{\sqrt{2\pi L}}\, e^{-(y-y_0)^2/(2L)} \qquad (1)$$

Here $\langle n_\pi^\pm\rangle$ denotes the mean pion multiplicity per collision, $dy = \frac{dp}{E}$ is practically equal to a relative energy bite.

The transverse momentum spread of pions is defined by the statistical distribution of their energy E^*: $\omega(E^*) \propto \propto \frac{1}{e^{E^*/T} - 1}$ inside a hydrodynamically moving volume element with a temperature T being of the order of pion mass m_π [5, 6c, 6d]. The full expression for momentum distribution looks like:

$$E\,\frac{d^3N_\pi}{d^3p} \cong \text{const} \int E^*\,\omega(E^*)\, e^{-(y-y_0)^2/(2L)}\, dy, \qquad (2)$$

with a constant providing with the proper value of $\langle n_\pi^\pm\rangle$.

Rapidity distribution from (2) is in a good agreement with (1) by L>>1 and y<L, the transverse momentum distribution:

$$\rho(p_\perp)\,d^2p_\perp \cong \text{Const}\ m_\perp \sum_{k=1}^{\infty} K_1\left(\frac{km_\perp}{T}\right) d^2p, \qquad (3)$$

where K_1 is the modified Bessel function and $m_\perp = \sqrt{m_\pi^2 + p_\perp^2}$, agrees well enough with a form: $\rho(p_\perp) \propto \exp(-bp_\perp)$, observed experimentally with $b \cong 6\ \text{GeV}^{-1}$ (the masses and momenta above are measured in energy terms).

In proton-nucleus collision the incoming proton interacts with a so called nuclear tube of a mass proportional to $A^{1/3}$ [6]. Due to that the pion spectrum occurs shifted by $\Delta y = -1/6 \ln A$ as compared to the pp spectrum. For the copper target $\Delta y = -0.69$. Maximum dN_π/dy for pCu collision with equal to 3 TeV proton energy E_p takes place near the pion momentum **p=2.8** GeV.

An account of energy dependent probability for pion decay during the acceleration results in effective shift of spectrum maximum to the high energy region. The number of pions of initial energy E and longitudinal momentum $p_\parallel$ is reduced during the acceleration up to an energy E_{fin} by a factor: $\left(\frac{E + p_\parallel}{2E_{fin}}\right)^\mu = \left(\frac{m_\perp}{2E_{fin}}\right)^\mu$ where $\mu = \frac{m_\pi}{c\tau_0\, dE/dx}$ with dE/dx standing for the accelerating rate and τ_0 - for pion life time. By insertion of this factor into (1) the effective spectrum is found to be:

$$(dN_{\pi}/dy)_{eff} \cong \frac{\langle n_{\pi}^{\pm}\rangle}{\sqrt{2\pi L}} \left(m_{\pi} \frac{\gamma^{1+\mu/2}}{E_{fin}}\right)^{\mu} e^{-\frac{[y-(y_0+\mu L)]^2}{2L}} . \qquad (4)$$

Its maximum is shifted by $\Delta y = \mu L$ that is up to $p = 5.4$ GeV/c in the pCu collision with $E_p = 3$ TeV by $dE/dx = 100$ MeV/m that is by $\mu = 0.18$. The whole number of pions is reduced by a factor of ~ 0.5 during the 2 TeV acceleration.

The transverse emitance of pion beam is found as $\varepsilon \sim \lambda \langle p_{\perp}^2 \rangle / p^2$ in dependence on nuclear absorption length λ, particle momentum p and mean square of its transverse component, which is equal to ~ 0.15 $(\text{GeV/c})^2$ for distribution (3) with $T = m_{\pi}$. At $p = 5.4$ GeV/c the emitance value, equal to ~ 0.4 mm.rad., exceeds by several orders the VLEPP linac acceptance. That means the pion momenta available to be captured into the linac are situated far away the production spectrum maximum. Fortunately the loss in capture efficiency is not very large because of a slow fall of spectrum density from the maximum with energy grow. That explains rather faint dependence of capture efficiency on acceptance value (fig. 1).

The energy bite of particle capture into the linac is defined by a width of stability region for transverse motion. The linac lattice is composed of FODO type elements with long drifts, occupied with the accelerating units, and quadrupoles as short as possible to keep high the average accelerating rate. The minimum drift length is equal to 1 m

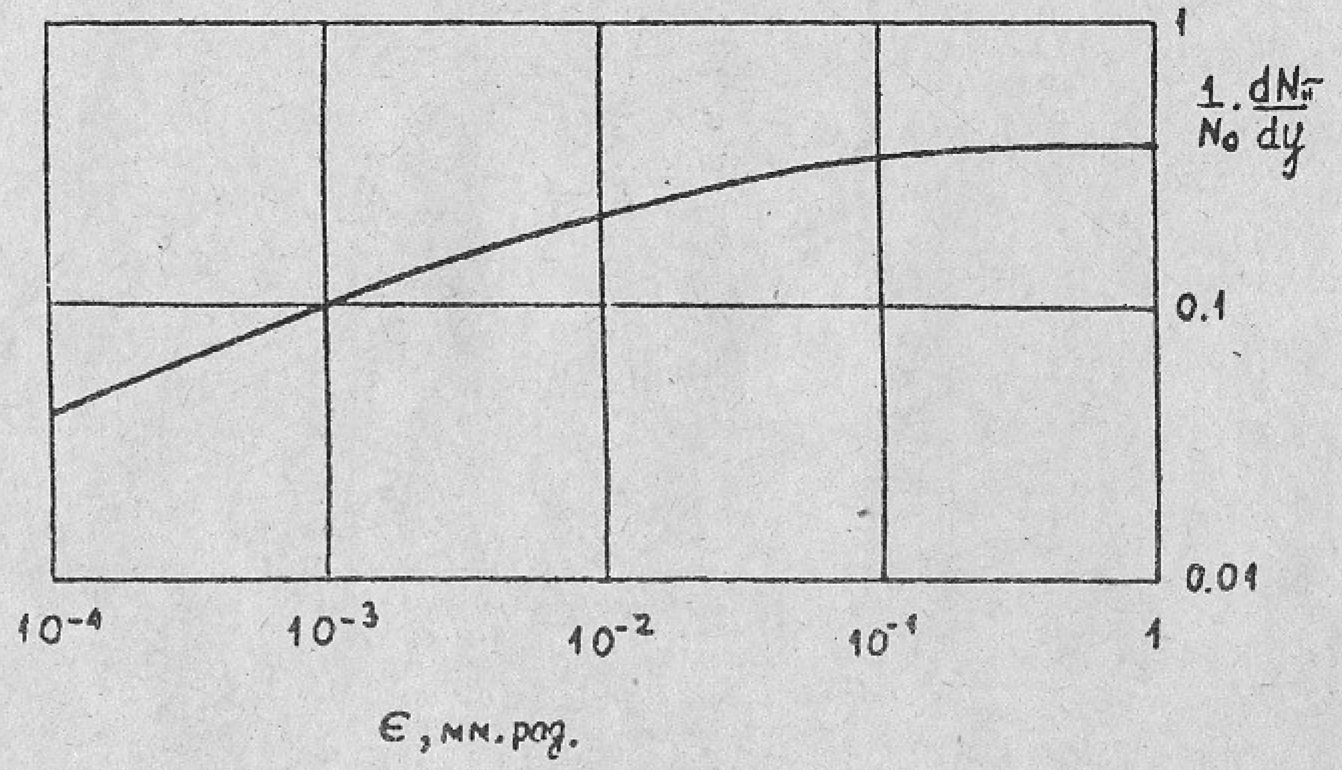

Fig. 1. Pion yield versus an emitance per relative energy interval per incident proton of 3 TeV energy with decay probability during the 2 TeV acceleration by $dE/dx = 100$ MeV/m included.

the length of one accelerating unit. Magnetic field gradient in quadrupoles is equal to 5 kOe/mm being confined by 1.5 T induction onto the pole tip and 3mm half-aperture. In figure 2 the maximum beta function in periodicity element is shown versus a quadrupole strength in terms of product kld with l standing for quadrupole length, d- for that of the drift and

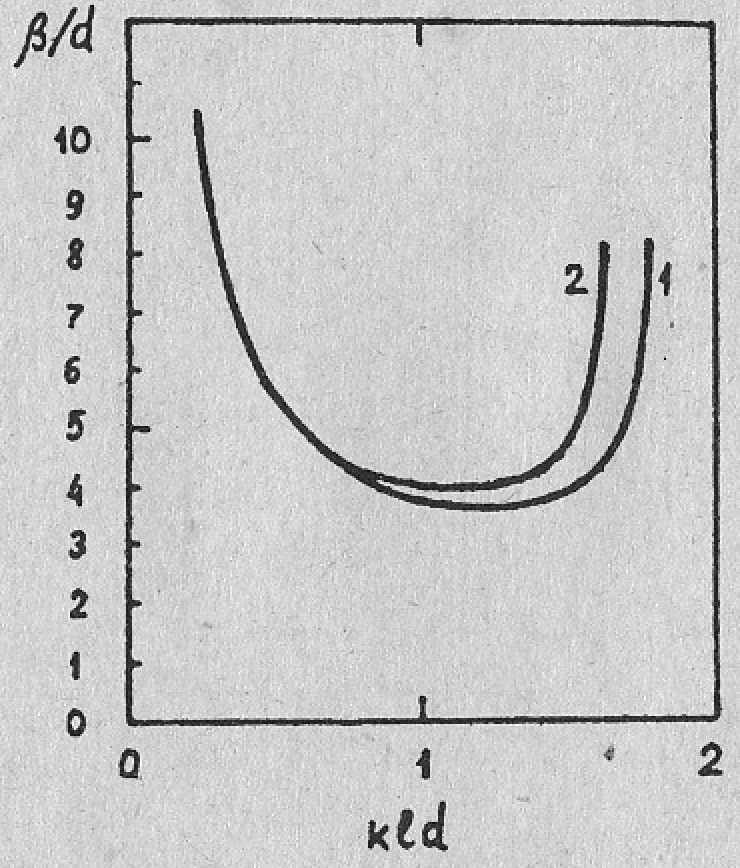

Fig. 2. Beta-function maximum in linac for l/d ratio equal to 0.1 (1) and to 0.2 (2) versus focusing strength in *kld* units.

k=egradH/pc. Ratios β/d for different l/d practically coincide that means the widening of captured energy bite and its displacement into high energy region in proportionality with quadrupole lengthening. The minimum captured energy is defined by l and d in meters like E_{min}, GeV = 100 ld. By an acceleration with l and d kept constant the beam is moving left along the curves fig. 2 so that the beta-function grows up almost in proportionality with energy grow and the beam size is conserved constant despite the emitance decrease. If the oscillation phase increment trough the periodicity element kept constant, i.e. the l and d are altered along the linac length in proportionality with $E^{1/2}$, the beta-function grows also as $E^{1/2}$ and the beam size is decreasing in proportionality with $E^{-1/4}$. That allows to make the aperture of linac reducing along with a rate up to that described as $a \propto E^{-1/3}$.

To match the pion beam emitance, having on target the effective beta-function of the order of $\lambda/2$, with the linac acceptance we use the lithium lens of 0.5 m focal distance. The lens being practically thin does not provide with the ideal matching in a wide energy bite accepted into the linac, but a big length of hadron target by short lens focal distance together with a wide angular spread of pion production compensate to a significant extent the chromatic aberration of lens focusing.

Shown in figure 3 are the spectra of pions and muons after the 2 TeV acceleration in both VLEPP linacs with equal to 0.25 l/d ratio. Mean collection energy is equal to 80 GeV - the optimum value for such a ratio. Relative energy spread in accepted beam is equal to ~ 0.5, the transverse emitance - to ~ $1.5\cdot10^{-3}$ mm.rad. Full number of accelerated pions is $N_\pi = 5\cdot10^{-2}$ per incident proton that with $3\cdot10^{14}$ protons in UNK means ~$1\cdot10^{11}$ pions per second inside ~2% energy bite

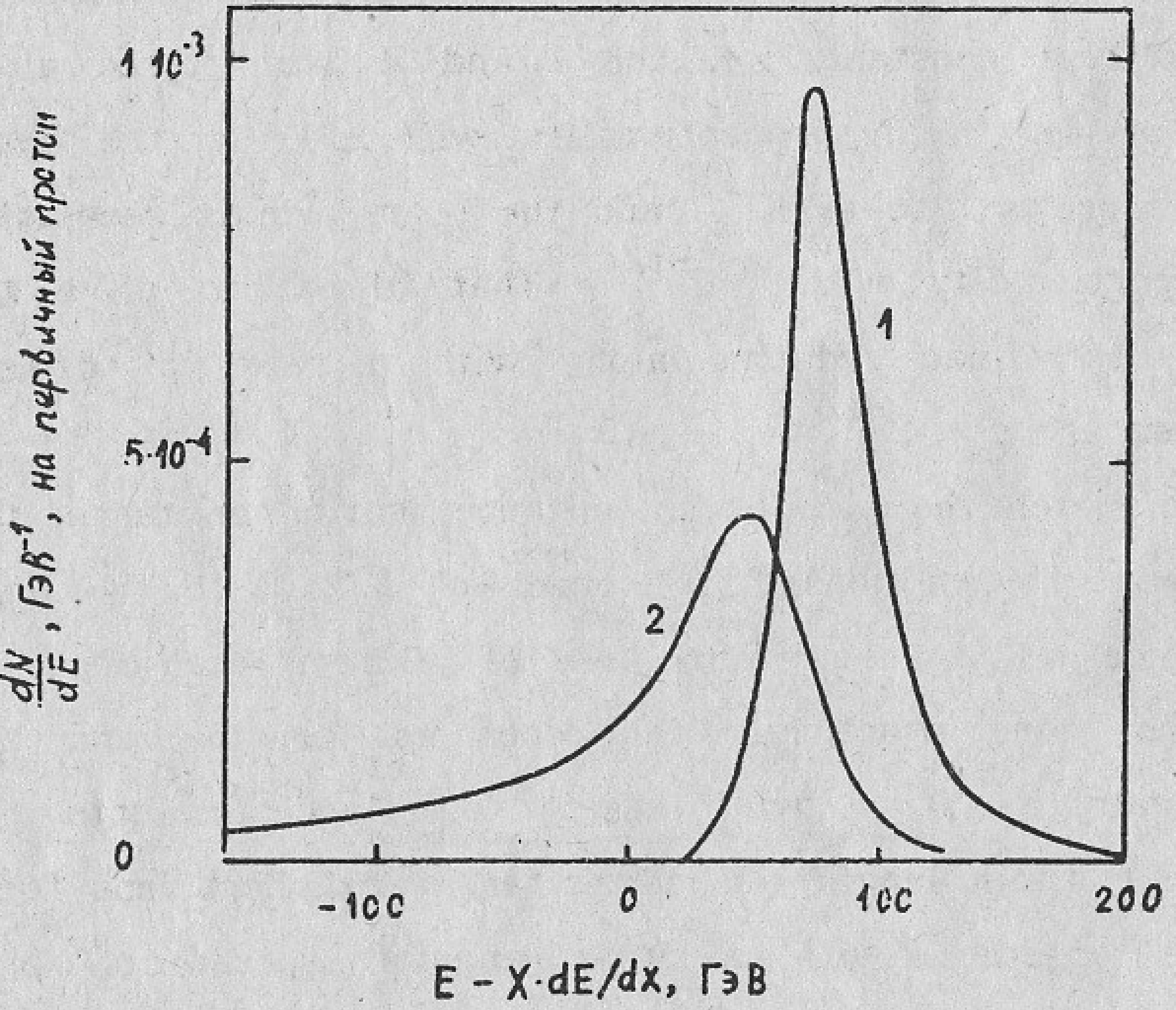

Fig. 3. Spectra of pions (1) and muons (2) after the 2 TeV acceleration. Quadrupole length l is equal to 0.25m, field gradient - to 5 kOe/mm, half-aperture a - to 3 mm. Drift length d is 1 m, and accelerating field- 100 MV/m.

and ~ $6\cdot10^{-5}$ mm·rad. transverse emitance. An efficiency for muon acception into the acceleration is close to unit. Muon spectrum density in the maximum achieves almost a half of pion spectrum density.

Dependence of accelerated pions number on collection energy is shown in fig. 4 for different values of l/d ratio.

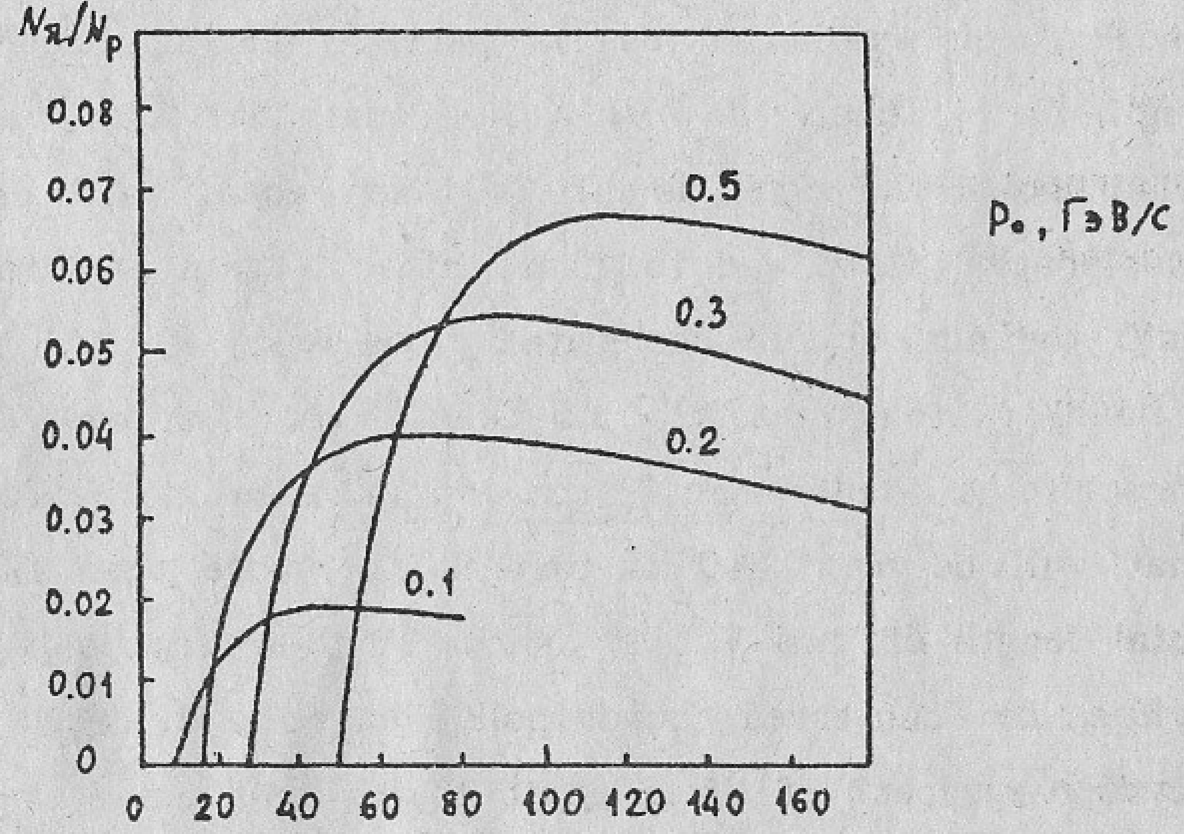

Fig. 4. Accelerated pion yield in dependence on the energy of particle collection from target for different l values (shown on curves in meters); d=1 m.

An increase in maximum N_π is seen in a wide range of quadrupole length grow. To utilize that without a significant loss in average acceleration rate the ratio l/d is to be made altered along the linac length - comparatively large at the beginning and being reduced with an increase of beam energy by means of drift lengthening. The lengthening is fulfilled by 1 m step - the accelerating unit length. To be recaptured into a new lattice the beam is to be accelerated up to an energy higher than minimum energy in it. Some dismatching in lattice functions by that is compensated by the decrease of beam emitance with an acceleration and so a loss in particle number occurs to be negligible. Thus, if with the equal to 0.5 m length of quadrupoles the drift length is taken equal to 1 m at the acceleration start and to 2 m after a gain of first ~ 100 GeV, the number of accelerated pions will be ~ $7.5\cdot10^{-2}$ per primary proton, that is ~ 1.5 times more than by l/d = 0.25 through the whole linac length. An increase in the former by that will be near 200 m that is not more than 1% of the total length of two VLEPP linacs. Further lengthening of the drifts by conserved quadrupole length will result in a further approach of linac length to its minimum - the sum of lengths of accelerating units.

Dependence of N_π on linac half-aperture a by kept equal to 15 kOe the maximum field H_{max} in quadrupoles, and on H_{max} by a kept equal to 3 mm are shown in figure 5 together with the dependence on a by kept constant the field gradient, i.e. by H_{max} varied in proportionality with a. It could be easily seen that at a = 3 mm and H_{max} = 15 kOe the yield of accele- rated pions though rather high occurs to be a small part of that produced in target.

To avoid the significant increase in energy spread

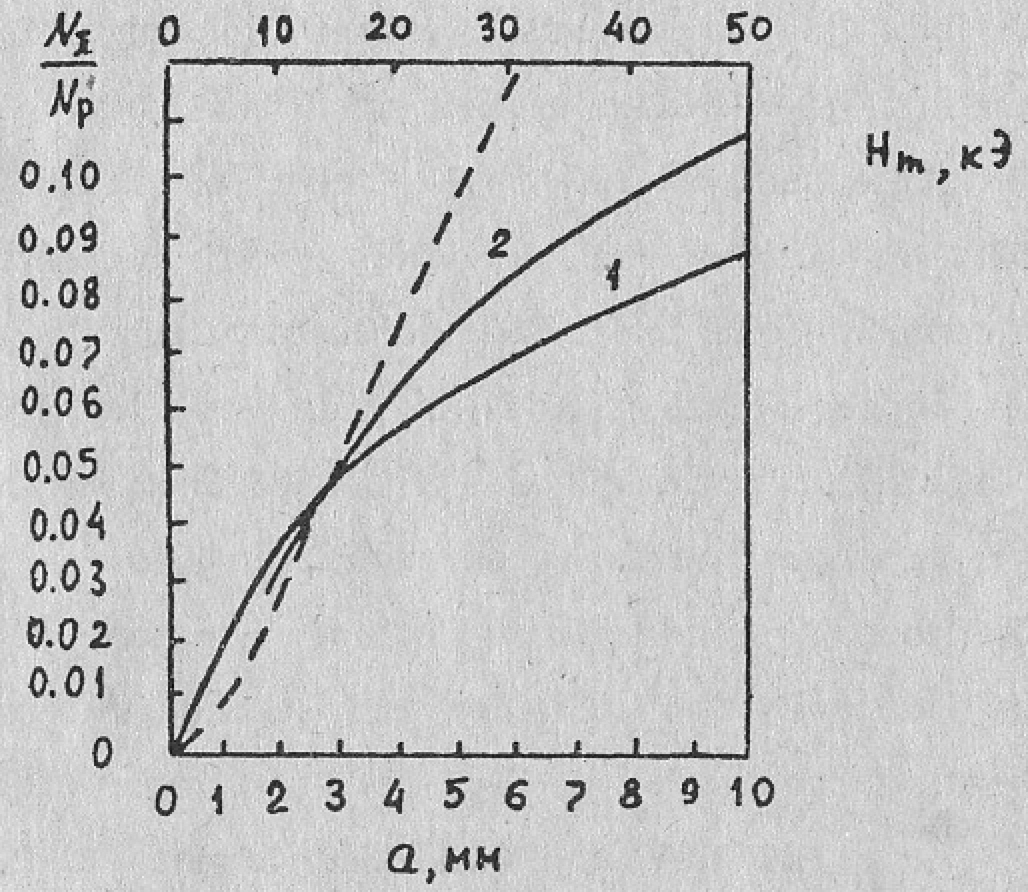

Fig. 5. Accelerated pion yield in dependence: 1 - on a by H_{max} =15 kOe, 2 - on H_{max} by a = 3 mm, dashed line - on a by grad H = 5 kOe/mm; l = 0.25 m, d = 1 m.

during the acceleration the bunch length in pion beam, equal to that in proton beam at the target, is to be made sufficiently short. The degree of proton bunching in the buncher is characterized (see Supplement) by a collection of ~ 70% particles into the bunches of $0.3\lambda_0$ length or ~ 55% - of $0.1\lambda_0$ length. The length ~ $0.1\lambda_0$ seems to be adequate to the angular and energy spreads captured into the linac. With homogeneous particle distribution inside them and 2 mm bunch length, the r.m.s. energy spread at linac exit will be equal to ~ ±20 GeV by a negligible bunch lengthening.

The technical problems in pion producing system are connected both with high energy deposition in target and thermal load in lithium lens. Passage through the target of all stored in the UNK protons for a time of ~ 100 s will result in released power of the order of 1 MW. The only possibility to remove such a power from a confined target volume consists in a use of liquid metal target - the melted lead or copper leaking with a high velocity through the energy deposition region - as a free jet from a long narrow nozzle - and then trough a heat exchanger [7].

The thermal conditions in lithium lens are defined both by energy deposition of primary and secondary beams and by Joule heating from current. The focal distance of 0.5 m for particle energy 80 GeV and collection angle ~ $5\cdot10^{-3}$ rad is provided by 15 cm lens length and 125 kA current amplitude. At a 100Hz repetition rate the Joule power will be of the order of 100kW inside a ~ 12 cm^3 operational lens volume. The heat removal will be fulfilled by means of liquid lithium pumping through the lens volume that will simultaneously provide with an intensive cooling of structural elements of the lens heated by beams.

One of the necessary conditions for pion acceleration in the VLEPP linacs consists in their protection from the primary proton beam a hit that would result in unacceptable level of radiation load in accelerating structures. Separation of primary and secondary beams could be achieved

by means of the achromatic bend by a small angle with two magnets disposed in a 100 m distance with a quadrupole doublet, placed in the middle to provide the pions of fixed energy with a half-wave focusing between the centers of magnets. With a bending angle of each magnet equal to $5\cdot10^{-3}$ rad., that by the order exceeds the pion angular spread, the quadrupole doublet half-aperture is to be ~ 6 cm for the energy bite ~0.5. With ~100 GeV particle energy the quadrupoles in doublet could be of ~ 2 kOe/cm gradient and ~ 2 m length.

Use for pion production of protons of lower energy - of the UNK "warm" ring 400 GeV energy, for instance, results in a less production efficiency but looks rather more adequate to the problem of pion acceleration in the VLEPP linacs because of the lower optimum collection energy, less optimum l/d ratio, significantly more simple the primary proton beam manipulation. Number of accelerated pions with Ep=400 GeV by ~ 50 GeV collection energy is equal to ~ $8\cdot10^{-3}$ per incident proton.

An efficient way for optimization of VLEPP linacs to gain the accelerated pions and muons yield consists in increase of aperture by conserved focusing rigidity. With half-aperture changed from 3 mm to 10 mm by kept equal to 5 kOe/mm field gradient and l/d = 0.25 the accelerated pions number is growing up to $N_\pi=2.4\cdot10^{-1}$ per incident proton that is by factor ~ 5. Such a modification of linac will, indeed, cause a big technical complications, connected with a grow of energy stored in accelerator structures and with a rise of magnetic field in quadrupoles significantly higher than the iron saturation level. All the more, rather slow decrease of emitance due to an acceleration from a comparatively high initial energy will not allow to get an enlarged aperture in a small part of linac length only.

In a conclusion let us briefly consider some of possible applications for pion and muon beams with above described parameters. For pions there are, first of all, the "far neutrino" experiments where the high energy and phase density in pion beam will provide with a density of neutrino flux and an accuracy for their detection unattainable with other pion sources. A possibility for pion-pion collision could also be considered though the luminosity attainable without a modification of VLEPP accelerating structures is not high. With compression of proton bunches both in UNK and external buncher (see Supplement) down to ~ 2 mm length the luminosity for pion-pion collision will be equal to several units by 10^{25} cm^{-2} s^{-1}. For muons the linear collision luminosity is several times less, however a comparatively large life time of accelerated muons, equal to ~ $2 \cdot 10^3$ revolution times in ~ 7T magnetic field, reserves in principle a possibility for multiple collisions of muon bunches.

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SUPPLEMENT

The system for bunching of continuous or quasi-continuous beam into short bunches, distanced by λ_0, consists of a linac section with wave length λ_0 and of bending tract. Coordinate dependent energy gain in the linac section together with an energy dependent length of particle way in the bending tract result in the bunching of particles from a beam length λ_0 around the one having zero energy gain in the linac section. In the linear approximation to longitudinal dispersion function in tract, $\Delta S(\Delta E) = -\chi_1 \Delta E/E$, the particle coordinate S in the beam's own frame after the buncher is:

$$S = S_0 - \chi_1 \Delta E_0/E \sin 2\pi S_0/\lambda_0$$

with So standing for the initial coordinate, ΔE_0 - for linac section energy and E - for beam energy. With homogeneous particle distribution along the primary beam, the optimum χ_1, resulting in the minimum mean square bunch length, is equal to $\chi_1 = \lambda_0/\pi\varepsilon_0$ with ε_0 standing for $\Delta E_0/E$. By that the value $\sqrt{<S^2>_{min}}$ with $<S^2>_{min} = \frac{\lambda_0^2}{2}\left(\frac{1}{6} - \frac{1}{\pi^2}\right)$ is equal to $0.18\lambda_0$. Inside such a size lie more than 70% of particles from the primary beam length λ_0. If the optimization of χ_1 is made only for a part of particles, though for a big enough one, the width of their coordinate distribution is much less (fig. 6). So, for 2/3 of particles the minimum r.m.s.

bunch length is equal to 0.09 λ_0 with got inside ~ 50% of primary beam particles.

Cubic term being added to longitudinal dispersion function in the tract with the optimum values for χ_1 and χ_3 will result in a shortening of bunch length but the effect is rather small. For all particles the $\sqrt{\langle S^2\rangle}_{min}$ is reduced down to $0.16\lambda_0$, for 2/3 of them - down to $0.038\lambda_0$.

To evaluate the bending tract parameters let us consider a tract consisting of a bending magnet with radius R and radial tune ν. In the magnet length an integer number j of free oscillation waves is to go to provide with zero finite gain in the transverse dispersion function ψ and its derivative ψ'. The longitudinal dispersion coefficient χ_1 is found by ψ integration over the bending angle $\chi_1 = \int\psi\, d\varphi$ and is equal to $\frac{2\pi jR}{\nu^3}$. The $\chi_1\varepsilon_0$ product is defined by the bunch length minimization; the ε_0 - to minimize the linac section length and the tract aperture, is to be chosen small although much more than an energy spread in a beam. That defines a choice of ε_0 ~ 1% and $\chi_1 \cong 0.6$ m. By that the tune is fully determined by magnet radius and oscillation waves number j. For j=1 with ~ 7T magnetic field and 3 TeV beam energy the tune is 25, tract length - 400m, bending angle - 14°, and magnet aperture - 5 cm. An increase of j by conserved χ_1 results in aperture decrease in proportionality with $j^{-2/3}$. Tract length by that increases in proportionality with $j^{2/3}$ and ν - with $j^{1/3}$.

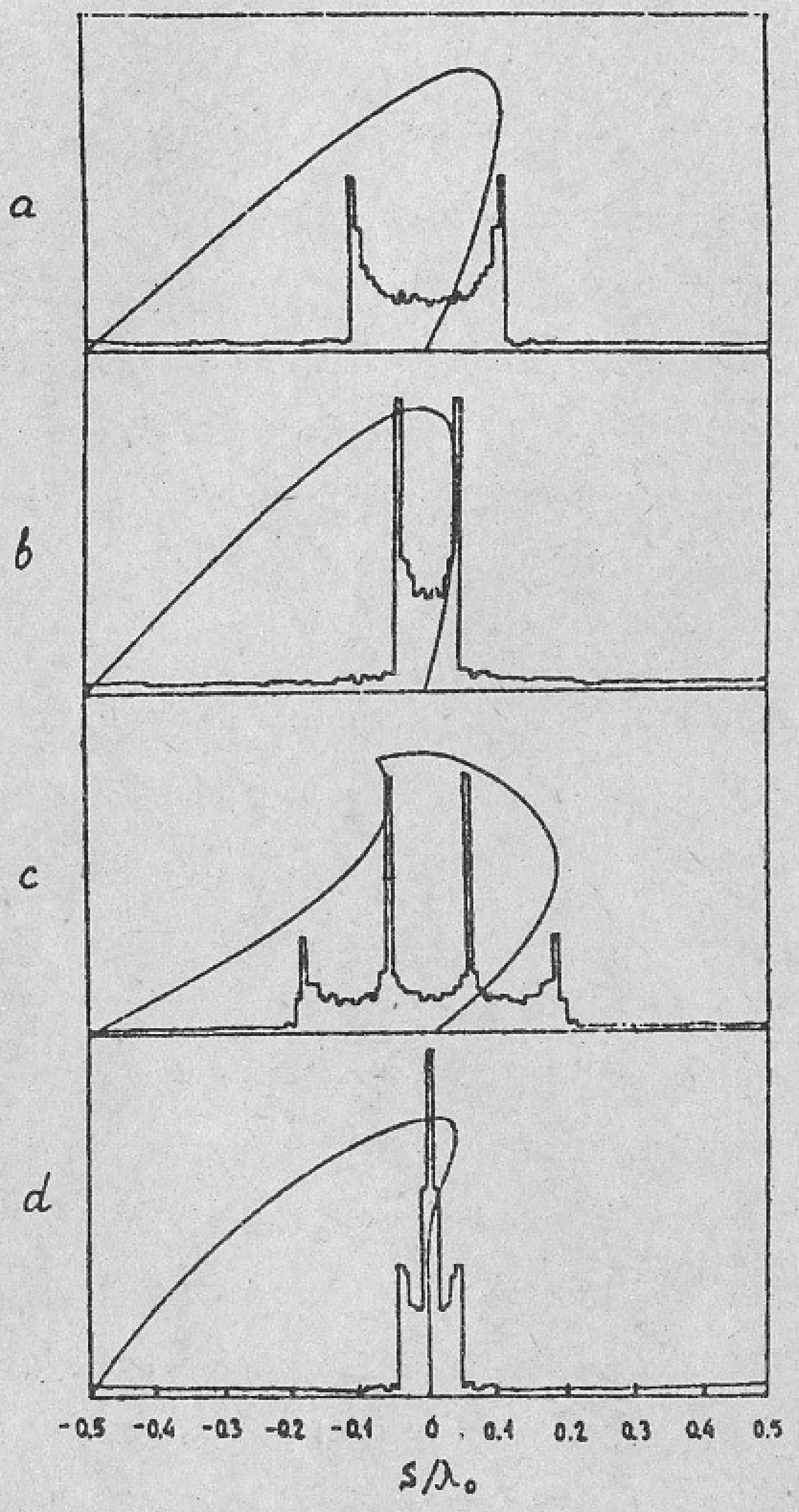

Fig. 6. Bunching efficiency: proton density distribution through a length λ_0, and longitudinal phase half-profile after the buncher for a beam with null initial energy spread; $a - \chi_1$ is optimum for all particles, $\chi_3 = 0$; b – the same for 2/3 of particles; $c - \chi_1$ and χ_3 are optimum for all particles; d – the same for 2/3 of particles.

For an example of real tract lattice, that consisting of FBDDBF cells could be considered with B standing for bending magnets and F and D - for quadrupoles, focusing and defocusing in the radial plane. If magnet radius and length are equal to 1500 and 15 m, accordingly, and quadrupole length - to 1.5 m by 10 kOe/cm magnetic field gradient, then twelve such cells will compose the one-wave tract with the longitudinal dispersion coefficient $\chi_1 = 64$ cm. The maximum of transverse dispersion function in the tract will be $\psi_{max} \cong$ $\cong 6$ m, the full length - 432 m. If the length of magnets is 7.5 m. and of quadrupoles - 1.1 m by 20 kOe/cm field gradient, the ψ_{max} is reduced down to 2.8 m, but the number of cells for the same χ_1 increases up to 48 (three oscillation waves) and the tract length- up to 935 m.

With a possibility for bunch-wise operation on proton beam, the UNK ring could be used as a bending tract for the buncher. The linac section in this case is located by-pass to the UNK drift and ejected bunch passed trough the section is injected again into the ring by means of a system similar to that for ejection. Longitudinal dispersion coefficient in UNK ring is of the order of 15 m per revolution, that is 25 times more than in above considered tracts and thus requires proportionally lower linac section energy, namely ~ 1.2 GeV instead of 30 GeV. With energy spread in a beam δE of several units by 10^{-5} and bunch length δl of $\sim 0.1\lambda_0$ that still meets the energy spread smallness condition: $\delta E/\Delta E_0 \sim$ $\sim \delta$

If the wave length of linac section could be made of the order of or more than the UNK proton bunch length, the former scheme provides with a proton bunch compression. For equal lengths of a wave and a bunch the compression efficiency is the same as for continuous beam bunching, but it is significantly higher when the wave is longer than bunch. So, with $\lambda_0 = 30$ cm and r.m.s. bunch length 10 cm, about 80% of protons could be collected inside a length of 2 cm. By that the compression could be fulfilled for several bunch revolutions in the ring that allows to reduce in proportionality the linac section energy from 10-12 GeV down to ~1 GeV - the minimum determined by the energy spread in a beam.

Pass of such formed proton bunch through the above described external buncher will result in its further compression till a collection inside the 2 mm length of ~55% of primary beam protons when $\lambda_0 = 2$ cm and of ~ 70% - when $\lambda_0 = 4$ cm.

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