ON PROTON BEAM EMITTANCE GROWTH IN LINAC

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The phenomenon of beam phase volume growth in acceleration process causes considerable difficulties in designing and operating high average beam current linacs. The emittance growth in linac-injectors of proton synchrotrons deteriorates the injection conditions.

This problem has been discussed in a number of papers [1-10], but however a unified theory embracing every aspect of this effect is not yet created. The existing experimental data are obviously insufficient and in many cases they are contradictory. This discrepancy is to some extent accounted for by the fact that the initial distribution is often measured at the linac input, while the emittance change in the matching channel remains uncontrolled. Besides, the final result is to a considerable extent influenced by different methods of data processing.

In our opinion it is very important to proceed with accumulating experimental data about the beam phase volume blow-up.

The linac I-2 belongs to one of the most intensive injectors with an output pulse current more than 200 mA. That is why the investigation of the beam phase volume blow-up with the help of this linac is of both practical and theoretical interest.

The measurements were carried out by means of two slits. The first measuring instrument was placed at the output of the preinjector in front of the buncher, behind which two quadrupole doublets of the matching channel could be found. Corresponding braking fields were created in the measuring instrument for reducing the influence of the secondary electron current. The input of the buncher and the input of the drift tube contained the beam current transformers. They were supplied with the variable aperture Faraday cups with the diameter equal to 38 and 20 mm correspondingly which were equal to the aperture of the subsequent part of the channel. The combination of the beam-current transformer with the variable aperture Faraday cup allows to measure the beam current incoming to the decreased aperture. The emittance of the beam at the linac input was estimated according to the data about the reduction of the beam current in the buncher and the first drift tube (DT-101). This evaluation is given below. The second measuring instrument after the linac also contained no lenses.

Fig.1a and 2a show the distribution of the equal phase-space density lines obtained respectively with the help of the first and second measuring instruments. Absolute emittances $E=\iint dx\,dx'$ were calculated in accordance with the figures limited by the equal phase-space density lines.

In order to make the comparison of input and output data more convenient absolute emittances were evaluated to the respective normalized value $V_n = \frac{\beta\gamma}{\pi} E$

The curves connecting the phase density values of the current $j = \frac{\Delta I}{\Delta V_n}$ with the values of the normalized emittances limited by the lines with the given density levels are dotted on Fig.1b and 2b. Let us call these curves subsidiary. The area of the figure limited by the axes coordinate and the subsidiary curve must be equal to the total current of the beam

$$I_{tot} = \int_0^\infty j(V_n)\,dV_n \qquad (1)$$

The dependance of the relative quota of the current which is contained in the given part of the normalized emittance on the value of the emittance (continuous curves Fig.1b and 2b) I/I_{tot} are determined by means of subsequent summarizing of separate parts of this figure

$$I = \int_0^{V_n} j(V_n)\,dV_n \qquad (2)$$

The curves

$$I/I_{tot} = f(V_n) \qquad (3)$$

give the distribution of the beam current versus emittance value.

It is necessary to point out the fact that the most important criterion of the precision of the carried out measurements is the coincidence of the total beam current values achieved by integration of the subsidiary curve and the total beam current obtained with the help of the direct measurements of the beam current intensity.

In order to evaluate the influence of the beam current intensity on the effect of the phase volume growth more than two tens of the current distribution at the linac input and output were divided into three groups depending on the beam current value in the first drift tube (I_{101})-Fig3a and in the second viewing chamber ($I_{\text{ІІ КН}}$) Fig.3b. The average distributions were made for each group. If one has a look at Fig.3 one will see that with the help of solid lines we depict the beam current average curves obtained in the first measuring instrument. For each curve we give the limits of the beam current change at the linac input (I_{101}). On Fig.3b you can see the average curves obtained in the second measuring instrument after the linac. The most considerable deflection of separately taken curves from the average distribution for each group did not exceed 3% for the beams with maximum intensity and reached 10% for the beams with the lower intensity. Taking into consideration this fact we shall use average curves of the beam current distribution for our further analysis.

The dotted lines (Fig.3a) give the evaluation of the beam current distribution just at the linac input.The dotted lines were obtained by means of evaluation of respective solid curves (Fig.3a). For this purpose it was necessary to determine the average ratio of the current incoming to the linac to the current measured at the viewing chamber corresponding to each distribution group at the output. The average ratio are given on Fig.3 with the help of the dotted horizontal lines and are marked by the same index as the average distribution curves. The aperture of the buncher limits the beam mainly in coordinates and the aperture of the drift tube (TD 101) limits it also in transversal velosities.Between the buncher and the linac input the matching quadrupole lenses - two doublets are placed.

The presence of optics to some extent causes the mixing of the particles.The optics transforms the outline of the emittance and approximates it to the matching form. That was why it was assumed that the particles in the external sphere of the emittance were cut off between the viewing chamber and the linac input. The total beam current just at the linac input is taken for 100% and the part of the current distribution in the emittance lying below the level of the cut-off was proportionally stretched. This resulted in the respective dotted curves.

While comparing the current distribution at the linac input and output (Fig. 3a and 3b) one can easily see that in the process of acceleration a considerable increase of the beam phase volume takes place. The dependence of the beam emittance at the linac output on its intensity in the range of estimation of the pulse current varying from 60 to 200 mA is not practically observed. However in case of a comparatively low intensity (curve1 on Fig.3b) one can see quite distinctly the expansion of the peripheral field of the beam in comparison with the beam kernel. Table I contains the average value of the current in the emittance 2mm·mrad at the linac output and respective value of the average phase density for each group for evaluation of the growth of the beam kernel phase volume. It is possible to compare the estimated groups at the linac input and output. Judging by Table I one can note that the phase density in the beam kernel at the linac output is lower than the average phase density of the beam just at the linac input and is equal to 1/4 that differs a little from the 1/3 that is a capture coefficient value.

Thus the phase density in the beam kernel goes down insignificantly, while the growth of the phase volume in 3-5 times is mainly due to the peripheral component of the beam. As the emittance of the beam at the linac input goes down with the reduction of the beam current (Fig.3b), the increase of the normalized emittance turns out to be greater for the lower intensity beam.

Fig.3c shows the evaluated current distribution curves in the emittance borrowed from paper[4]. Curve I corresponds to the even distribution of the phase density on the surface and is close to the experimental current distribution at the linac input, curve 5. Curve 2 was obtained by means of projecting to the phase plane of the four-dimension hyperellipsoid with the even distribution of phase density in the hyperellipsoid volume. Curve 3 corresponds to the projection of the six dimensional hyperellipsoid with the even distribution of density in the six dimensional space. Curve 4 corresponds to (according to the terms used by the authors of paper [4]) Gaussian distribution of phase density on the plane that is it is an exponent. Finally dotted curve 6 corresponds to the average distributions at the linac output (Fig.3b). Experimental curves 5 and 6 were given to scale of the evaluated curves 1-4 by means of equalizing of the initial slope.

The comparison of the experimental current distribution (dotted curve 6) with the evaluated curves (Fig.3c) shows that the average distributions for the high pulsed intensity beams at the linac output are most close to the curve corresponding to the even distribution of the density in the six-dimensional hyperellipsoid volume.

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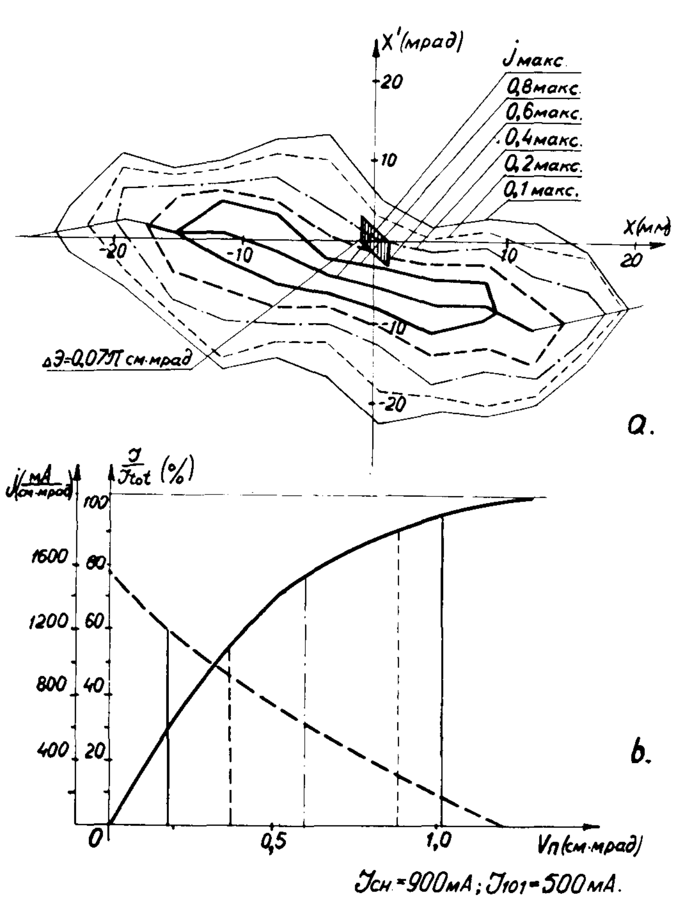

Fig. 1 a) Plots of the equal phase-space density lines for the beam at the preinjector exit.
b) A phase-space density and percentage of the preinjector current distributions versus emittance value.

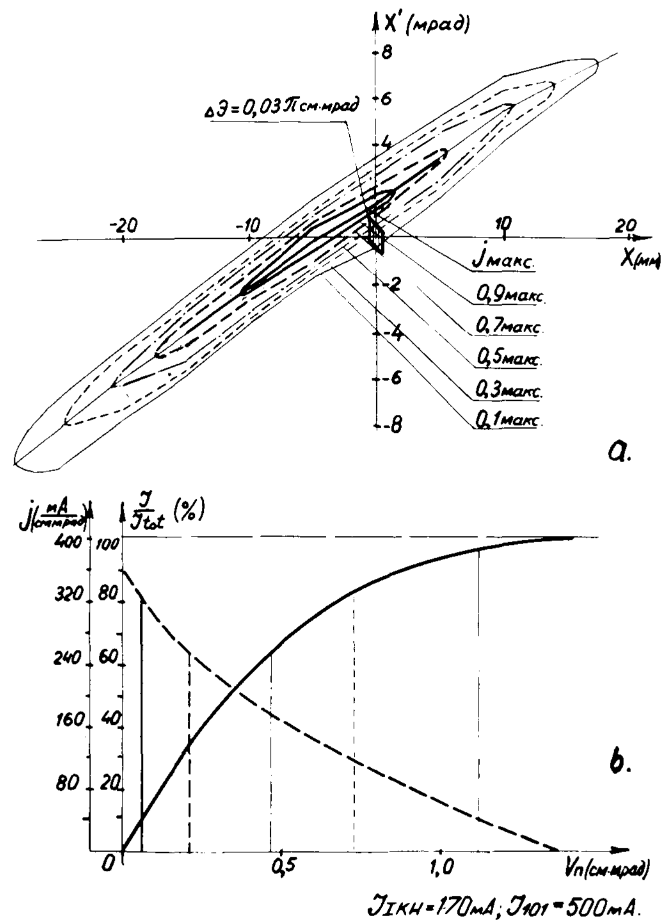

Fig. 2 a) Plots of the equal phase-space density lines for the output linac beam.
b) A phase-space density and percentage of the output linac current distributions versus emittance value.

Table I

LINAC INPUT			LINAC OUTPUT				
Full Current mA	Emittance norm. cm·mrad	Phase density mA/cm·mrad	Full Current mA	Current in emittance less than 0.2 cm·mrad	Phase density in the beam kernel mA/cm·mrad	Capture	Reducing of phase density
175	0.25	700	80	35	175	0.46	0.25
380	0.38	1000	130	47	235	0.34	0.24
535	0.43	1250	180	65	325	0.34	0.26

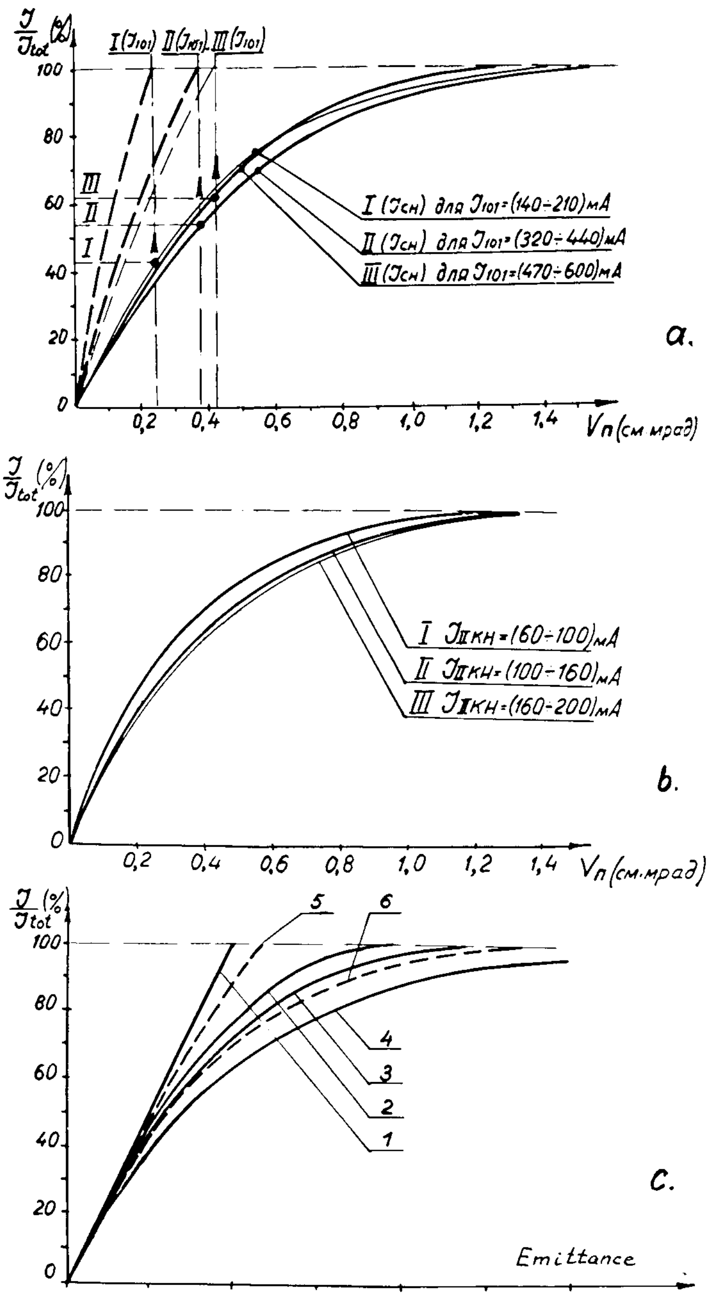

Fig. 3 a) Average distributions of the input linac current versus emittance value.
b) Average distributions of the output linac current versus emittance value.
c) A comparison of the various beam current distributions versus emittance value of calculated date (solid lines) and measured date (dotted lines). The interpretation of the curves there is in the text.