ANALYSIS AND SYNTHESIS OF ELECTROSTATIC FOCUSING AND ACCELERATING DEVICES WITH THE HELP OF KAPCHINSKIJ-VLADIMIRSKIJ "MICROCANONICAL" BEAM MODEL

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Due to its simplicity the Kapchinskij-Vladimirskij "microcanonical" beam model (MCB) [1,2] allows us to receive in a few seconds the results of computation when varying both beam parameters and beam forming devices; thereby it enables us to analyze plenty of different proposals, that is especially important when solving problems at their first stages. And visualization of MCB computation results reveals common, the most essential features of the problem considered and shortens a path to achieve the purpose. MCB approximation laconically allows for basic parameters of beam: current and emittance (ellipse area, divided by π; ellipse confines projection of transverse phase space of beam particles on X, X′ phase plane; ellipse configuration strictly determines the radius and slope of beam envelope).

For the MCB a current density in a cross-section of a beam and a phase density inside the phase ellipse are constant. The MCB unique property (non-distortion of the ellipse in linear forming devices) allows to make calculations in "reverse direction", i.e. from the receiver of a beam back to its source, and to find required conditions for the optimum matching of a beam emittance with the receiver acceptance.

For linac the x-axis equation of MCB envelope is [2]

$$\frac{d^2 r_x}{d\tau^2} + Q_r(\tau) r_x - \frac{F_x^2}{r_x^3} - \frac{2r_a^2}{r_x + r_y} = 0,$$

where r_x and r_y are the envelope radii of x and y axes, Q_x is the x-axes strength projection, $d\tau = (V_s/S)dt$, V_s is the synchron particle velocity, S is the focusing field period, $r_a = S\sqrt{2I/(\beta^3\gamma^3 I_0)}$, I is the beam current, $I_0 = 4\pi\varepsilon_0 m_0 c^3/e$, for proton $I_0 = \pi 10^7$A, F_x is the x-axis projection of transverse emittance.

Identical equation is for the y-axis.

For electrostatic devices in paraxial approximation envelope of nonrelativistic rotational-symmetric MCB is determined by

$$\frac{d^2 r}{dz^2} + \frac{1}{2U}\frac{\partial U}{\partial z}\frac{dr}{dz} + \frac{1}{4U}\frac{\partial^2 U}{\partial z^2} r - \frac{F_u^2}{r^3} - \frac{A}{r} = 0,$$

where Z is the beam axis coordinate; U is the axis potential corresponding to particle energy; $A \sim \sqrt{m/e}$, for protons $2.57\cdot 10^{-2}\cdot I/U^{3/2}$[mA/kV$^{3/2}$]; $F_u^2 = F_0^2 \cdot U_0/U$; F_0 is the emittance measured for particle energy corresponding potential U_0.

In most applications satisfactory accuracy is obtained when substituting the true potential path for broken line, i.e. when approximating the path by a number of lengths with constant acceleration (or drift) and thin lenses on length boundaries.

The concrete MCB applications for accelerating and beam forming devices with a rotational symmetry are given below.

For the pulsed neutron generator ING-2 [3] the 300kV accelerating tube was designed. It accelerated nearly 100mA of deuterons. The problem of optimum matching of an ion source having the 19 mesh honeycomb extraction system with the solid tritium target was solved with the help of the MCB computation. As a result of synthesis the construction with 3 accelerating gaps and 2 drift space intervals between them was selected; these elements have lengths of 31, 25 and 38mm (numeration originates from the ion source) and 460 and, respectively. Accelerating voltage is uniformly distributed between gaps; first gap represents lens consisting of the cylinder ∅140mm and the grid, second – two cylinders ∅200mm and third – the cylinder ∅140mm and the grid.

In this case the MCB-model was very close to the actual beam, because the ion source produced practically a uniform density of particles in the beam cross-section. The tube construction, performed in accordance with the results of computation, provided the adequate focusing of a beam and no device modifying was required.

The analysis of focusing properties of the accelerating tube (AT) of the MMF linac proton injector has been carried out. The accelerating tube has previously been described [4, 7].

The accelerating tube has a following construction. Particles enter in AT field with the energy corresponding to the extraction voltage. Extraction electrode is a grid with the ∅35mm confining aperture. The first accelerating gap consists of the ∅140mm cylinder and grided electrode separated by 100mm space. The grided electrode aperture is ∅190mm. Distance between the grid and the extraction electrode is 280mm. Just this gap basically forms the beam, makes its radius and slope to be sufficient for matching with the LEBT channel input. In general, the second gap with 450kV potential difference represents uniform field with slight focusing; there is a ∅70mm diaphragm at theAT end.

For the formerly selected injector operation mode with U_{ex}= 20kV, U_{foc}= 30kV the sets of beam envelopes have been obtained at different initial values of the beam radius and envelope slope (Fig. 1).

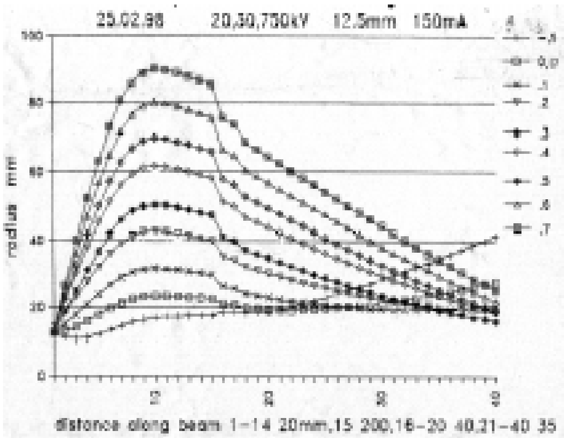


Fig. 1. Dependence of beam envelope on its initial slope.
Initial radius of envelope is 12.5mm, beam current is 150mA, normalized emittance is 1,5π·mm·rad.

In the set of envelopes only those which have dimensions less than the confining diaphragms (in the extraction electrode ∅35mm, the AT electrode with the grid ∅190mm, the AT output diaphragm ∅70mm and the LEBT channel input ∅50mm) can be realized. So, we obtain the set of permissible envelopes, which are shown in Fig. 2 for two modes of focusing: 24 and 32kV. The region for the 24kV value is much wider and there are more envelopes inside the confining diaphragms.

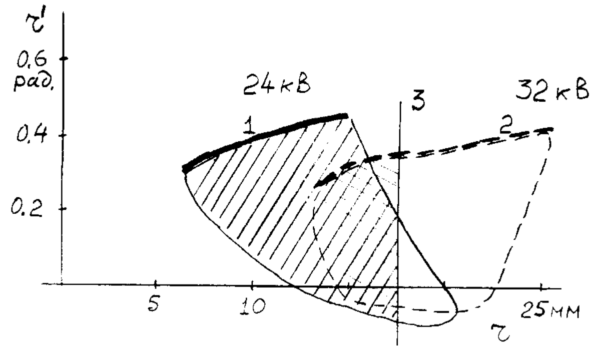


Fig. 2. The permissible spaces of the initial values for the proton injector AT envelopes.
Beam current - 150mA. Normalized emittance is 1,5π·mm·rad. Extraction voltage is 14,5kV. Curves: 1 - the region for 24kV focusing voltage; 2 - the region for 32kV focusing voltage. Straight line 3 is the output diaphragm radius in the extraction electrode. Bold-faced lines are confined by the AT output diaphragm; thin lines are confined by the LEBT channel input.

The beam envelopes were computed in the same way when decreasing the AT voltage. The following beam currents are calculated: a) in the induction pick-up located at the 1400mm distance from the AT output after the 50mm beam size confining diaphragm; b) on the insulated diaphragm at the AT end ∅70/∅150mm. The results are shown in Fig. 3.

In spite of rather strong assumptions of the MCB model, the experimental values are close to the calculated curves, which confirms the usefulness of the MCB for analysis and such problems, as current transmission and beam current confining. Moreover, from accordance with experimental value it is possible with confidence to say that envelope slope is close to value 0.0rad at AT input.

It is interesting to compare the MCB computation results with the modified «particle-in-cell» model of calculations which is more detailed and precise but require more than an hour, for example, when using the KOBRA-3 code [5].

Fig. 4 shows the envelopes for three beams with different values of emittance in the focusing electrostatic system which consists of three sequential lenses; each lens represents ∅60mm cylinder between grounded grids. Intervals between grids are 76mm, cylinder length is 40mm, positive potentials are applied to these cylinders. Intervals between the grids and the cylinders are 18mm [6]. Curves are the MCB computation, dots are the KOBRA-3 one. It can be seen that the MCB model correctly reproduces the main focusing properties even in this complex system.

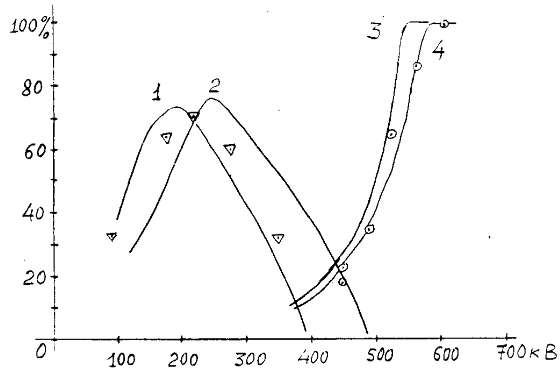


Fig. 3. Dependence of the AT calculated currents on the AT voltage.
The currents on the diaphragm at the AT end: 1 - initial slope of an envelope is 0,0rad; 2 - slope is 0,15rad. The currents in the induction pick-up: 3 -slope is 0,15rad; 4 - slope is 0,0rad. Dots are experimental values. Beam parameters: current is 150mA; extraction voltage is 14,5kV; focusing voltage is 24kV.

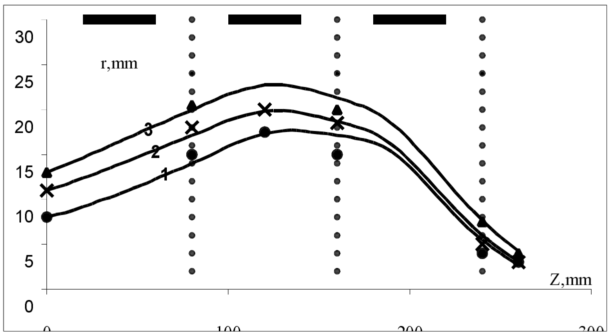
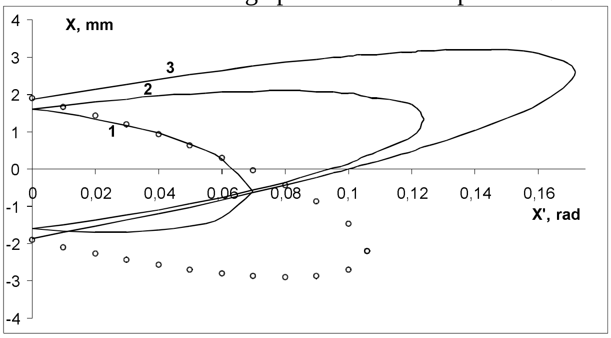


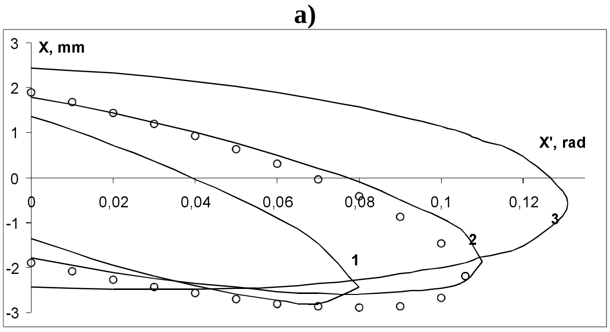
Fig. 4. The MCB envelopes for the system of 3 electrostatic lenses with grids.
Current of Ta^{+20} ion beam is 60mA; particle energy is 20x60keV. Curves: 1 - initial radius is 8mm; emittance is 0,2π·mm·rad; lens voltages (beam direction) are 7, 30, 45kV; respectively: 2 - 11mm; 0,32π·mm·rad; 7, 28, 40kV; 3 - 13mm; 0,5π·mm·rad; 7, 26, 36kV. Dots are the KOBRA-3 code simulation.

Beam-acceptance matching by means of MCB is illustrated in Fig.5. The system contains 3 grounded cylinders (diameters are 60, 60 and 30mm, and lengths are 40, 40 and 20mm) and 2 grids having -45kV potential. Distance between the grids is 76mm, ones for the big cylinders and grid are 18mm and one for the small cylinder and the grid is 9mm. Real beam is approximated by 3 MCB which model center and mediate parts and whole beam with current 100, 140 and 160mA accordingly. The emittance contours show that Fig.5b conditions are rather good.

Thus the MCB model is very good and useful tool for study of electrostatic forming and accelerating devices. Allowing for essential parameters of intensive beam focusing (current, emittance, configuration of emittance contour in phase space) model gives us correct results for a large part of the beam particles.



a)



b)

Fig 5. Emittance contours of 60keV proton beams after passing through focusing system.
Beam parameters: 1 - initial radius is 6,3mm; slope is 0,04rad; emittance is 0,11π·mm·rad; current is 100mA; accordingly: 2 - 9,0mm; 0,057rad; 0,2π·mm·rad; 140mA; 3 – 11mm; 0,07rad; 0,32π·mm·rad; 160mA. Drift spaces are: a) 45mm after system; b) 20mm before and 50mm after system.

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