

# DEVELOPMENT OF WIRE-MESHED ELECTROSTATIC LENSES FOR PROTON LINAC

V.V. Kapin<sup>\*</sup>, B.Yu. Bogdanovich, A.V. Nesterovich,  
V.V. Yanenko, MEPHI<sup>#</sup>, Moscow, Russia

## Abstract

The 2-MeV 150-MHz proton RFQ linac is set up at the Radiation-Acceleration Center (RAC) of Moscow-Engineering Physics Institute (MEPHI). Its output beam-line contains doublet of the electrostatic focusing lenses with a novel design featured by the two-dimensional electric field and wire-meshed beam apertures. Every lens provides a transverse focusing effect only in one plane, while does not affect on the beam in a perpendicular plane. In this report, the analytical and numerical analysis of this lens is presented. The optics of output beam-line including these lenses is evaluated with TRACE-3D code. The experimental construction of the lens doublet is presented.

## INTRODUCTION

The 2-MeV 150-MHz proton RFQ linac [1] is set up at RAC of MEPHI. It serves as a base system for the applied research works. Its output beam-line consists of doublet of the electrostatic focusing lenses, the post-accelerating 7-gap two-ridge interdigital H-resonator and a magnetic C-shaped spectrometer with vertical magnetic field.

Initially, the output beam-line with focusing doublet of two magnetic quadrupoles (instead of electrostatic lenses) had been simulated with TRACE-3D code [2]. It was shown [3] that the beam transmission is less than 10% without a focusing doublet, and it can reach 100% at the optimal magnetic field gradients of 6-7 T/m.

Although these gradients are quite moderate for a modern technology, a fabrication of quadrupoles may require impermissible efforts and resources for our small experimental setup. Therefore, the alternative focusing system based on wire-meshed electrostatic lenses had been proposed. In this report, the features and status of doublet of the electrostatic focusing lenses are presented.

## WIRE-MESHED ELECTROSTATIC LENS

### General Scheme of the lens

An unconventional design of the electrostatic lens featured by the two-dimensional electric field and wire-meshed beam apertures is proposed. Figure 1,a shows the ideal 2D-layout of such lens, which consists of two plane electrically-grounded wire-meshes located at planes  $z=\pm l/2$  and two (upper and lower) high-voltage ( $U_m$ ) cylindrical electrodes of radius  $R$  located at distance  $a$  from  $z$ -axis. The 3D model of the lens and the distribution of electric potential in the lens cross-section at  $x=0$  are shown in Fig.1,b and Fig.1,c, respectively.

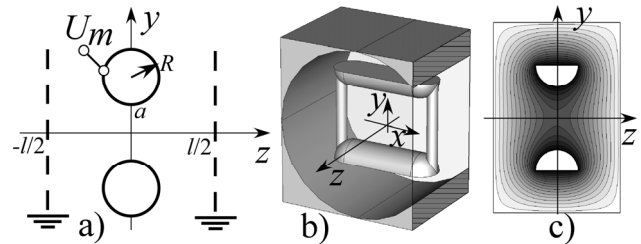


Figure 1: Layout of wire-meshed electrostatic lens: a) 2D ideal layout; b) 3D model; c) potential at  $x=0$ .

Such lens provides a transverse focusing effect only in one plane (the YOZ-plane in Fig.1), while does not affect on the beam in a perpendicular plane (the XOZ-plane in Fig.1). The pair of such lenses rotated by 90-degree relatively each other can provide an independent focusing in both transverse planes.

### Focal distance evaluation

Let's evaluate the focal distance in a this-lens paraxial approximation according to the formulae

$$f_y = y_0 / \text{tg}(\alpha_y) \approx y_0 / \alpha_y, \quad (1)$$

where  $y_0$  is the transverse particle coordinate at the lens center and  $\alpha_y \approx \Delta v_y / v_z$  is the angle kick provided by the lens. Let's neglect deviations of the longitudinal velocity  $v_z$ . Then, the increment of the vertical velocity  $\Delta v_y$  can be expressed as

$$\Delta v_y = \frac{q}{m_0 \gamma_z} \int_l E_y \cdot dz, \quad (2)$$

where the integral can be treated as a transverse lens voltage  $U_y$ . Note, that the transverse voltage can not exceed the electrode potential

$$U_y = \int_l E_y \cdot dz \leq U_m. \quad (3)$$

Finally, the angle kick  $\alpha_y$  is expressed as

$$\alpha_y = U_y / (W \beta_z^2), \quad (4)$$

<sup>\*</sup>kapin@mail.ru

<sup>#</sup>National Research Nuclear University "MEPHI"; <http://www.mephi.ru>

where  $W = m_0 c^2 \gamma / q$  is particle energy, and  $\beta_z$  is the relative velocity. Let's note that  $\alpha_y$  strongly depends on  $\beta_z$  decreasing inversely as the square of  $\beta_z$ , and is proportional to  $U_y$ , which will be evaluated below.

### Evaluation of Minimum focal distance

In linear this-lens approximation, the focusing distance of this lens can be evaluated assuming a maximum value of  $U_y \approx U_m$ , which can be reached at  $y_0 = a$ . Then, the focal distance is expressed as

$$f_y^{\min} \approx W \beta^2 a / U_m. \quad (5)$$

Let's evaluate  $f_y^{\min}$  for protons at RFQ exit. There can be two portions of protons, namely the accelerated ones with the energy of 2-MeV and the non-accelerated ones with energy of 0.1 MeV. For 2-MeV protons (the total energy  $W=940$  MeV and  $\beta=0.066$ ) the lens with the radius of aperture  $a=1$ cm and the voltage  $U_m=100$ kV can ensure the focal distance about 0.4 m. For 0.1 MeV protons the focal distance is much smaller and is equal to 0.05 m. It is clear that the lenses can work as supplementary energy filter for low-energy protons.

### 2D analytical formula for $U_y$

Assuming 2-D ideal geometry analytical formula for the potential distribution  $U(y, z)$  can be derived [4]. Applying the boundary conditions  $U(0, \pm l/2) = 0$  and  $U(a, 0) = U_m$ , the lowest-order potential can be written in the following form [4]:

$$U(y, z) \approx U_m \frac{\text{ch}(\pi y/l)}{\text{ch}(\pi a/l)} \cos(\pi z/l). \quad (6)$$

Then, the transverse lens voltage is expressed by the following formula:

$$U_y(y) = -2U_m \frac{\text{sh}(\pi y/l)}{\text{ch}(\pi a/l)}. \quad (7)$$

Note, that the equation (7) does not take into considerations higher harmonics of a potential, which are important to express the potential distribution for a realistic configuration of the lens.

### 3D numerical calculations of $U_y$

The 3D numerical calculations has been performed for a realistic lens geometry at the electrode voltage  $U_m=1$  kV. The horizontal electrodes with the radius  $R=10$  mm and the length of 60 mm are located in the cylindrical tank with the radius of 45 mm and the length

$l=60$  mm (see Fig.1). The 3D-simulated potential and electrical field distributions along  $z$ -axis are shown in Figure 2.

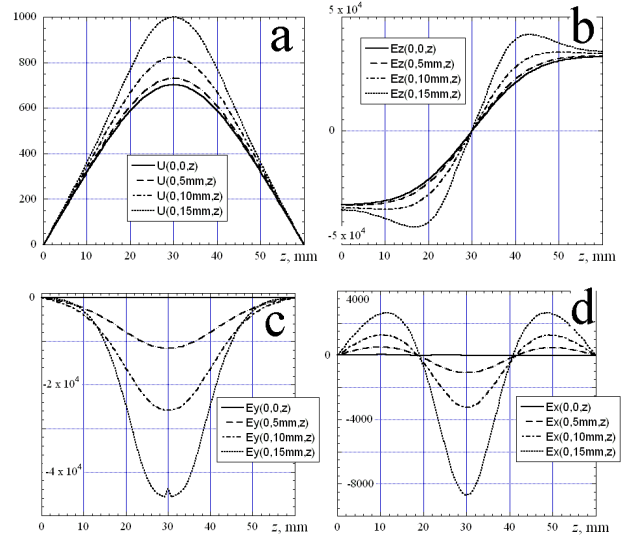


Fig.2. The potential and electrical fields vs  $z$  :

- $U(0, y_0, z)$  at  $y_0=0, 5, 10, 15$  mm;
- $E_z(0, y_0, z)$  at  $y_0=0, 5, 10, 15$  mm;
- $E_y(0, y_0, z)$  at  $y_0=0, 5, 10, 15$  mm;
- $E_x(x_0, 0, z)$  at  $x_0=0, 5, 10, 15$  mm;

The numerically calculated transverse potential distributions  $U_y(y)$  and  $U_x(x)$ , and  $U_y(y)$  calculated with eq.(7) are shown in Fig.3. Note, that  $U_x \ll U_y$ , and the expression (7) describes  $U_y(y)$  well at  $y \ll a$ .

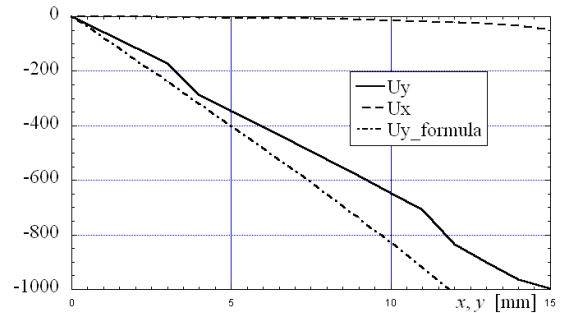


Fig. 3 The transverse potential distributions:  $U_y(y)$  -numerically and analytically calculated,  $U_x(x)$  -numerically calculated.

### Beam optics evaluations

The beam transport in the output beam line has been evaluated using the TRACE-3D code [2]. The simulated beam-line consists of two exit RFQ-cells, the wire-meshed electrostatic lenses, the 90°-bending magnet with zero field-gradient index and input and exit edges simulating the magnet fringe-fields, while all components

separated with appropriate drift-spaces. In these simulations, the focusing effects of 7-gap IH-structure are neglected, and structure is simulated by the drift-space. Thus, beam focusing in this beam-line is ensured by electrostatic lenses and the magnet fringe-fields.

The beam dynamics simulations are shown that without any focusing (the electrostatic lenses and fringe-fields are off) the beam transmission in the whole output beam-line is very low (about 2.5%). When the fringe-focusing is used, the beam transmission is increased up to 7.5%, which is still very low. Only with usage of doublet of

lenses, it is possible provide the 100% beam transmission. Figure 4 shows the beam phase-spaces at the input and output of the beam-line and the beam envelopes along the beam-line.

In the calculations, the doublet of the wire-meshed electrostatic lenses with total length of 120 mm is located near to the RFQ-exit at the distance 200 mm. The focal distances of the lenses are equal to 0.4 m, which corresponds to  $U_m=100\text{kV}$ . Practically, this voltage can be taken from high-voltage terminal of ion source.

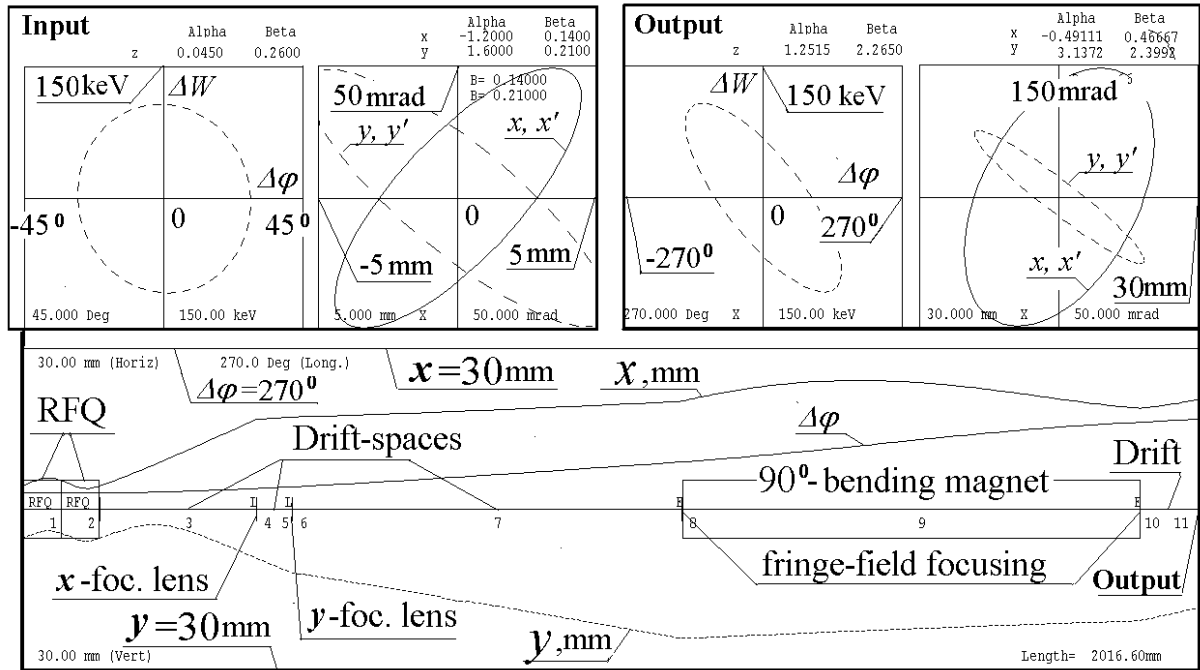


Fig.4 Beam phase-spaces and envelopes calculated by TRACE-code.

*The construction of the lens doublet*

The doublet of the wire-meshed lenses has been constructed, fabricated and tested at the maximal electrode voltage  $U_m=100\text{kV}$ . Figure 5 shows a general view of the fabricated doublet of the wire-meshed lenses.

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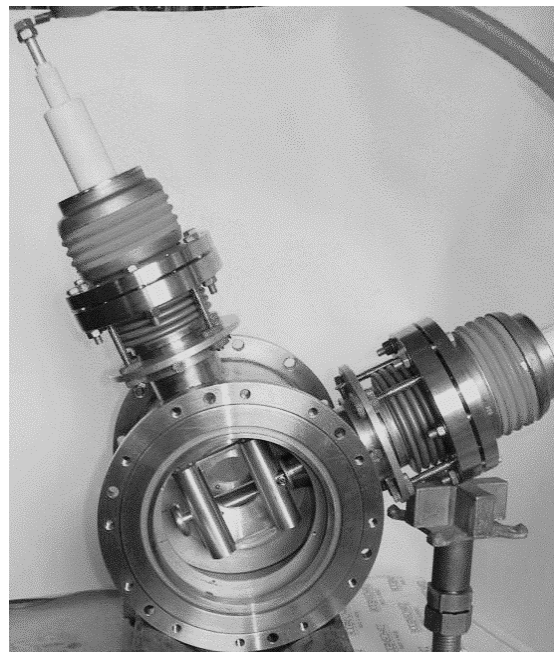


Fig. 5 General view of the wire-meshed lenses