

OPTIMIZATION OF QUADRIPOLE FIELD PRODUCTION FOR ELECTROSTATIC ION BEAM FOCUSING

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Abstract

Recent calculations concerning the quadrupole shape used as a focusing lens revealed a potential progress margin concerning the optical performances especially for devices with a small length over aperture ratio. The main issues of the paper are related with the improvement of some standard quadrupolar focusing equipment considered here with an electrostatic technology i.e. with the influence on the beam transmission, aberrations limitation, and reduction of beam losses. The joint research and development programme between a laboratory and the industry are expected to enable technology transfer, design optimization and cost reduction.

INTRODUCTION

The need to improve and optimize the electrostatic quadrupole design used for the focusing of high-power and radioactive ion beams is created by the search of a good transmission, the safety issue and cost-effectiveness [1, 2]. The last point will be managed in the frame of a partnership with an industry and thanks to its know-how. The developments performed together led to the results described in this paper devoted to the session for industry, technology transfer and industrial relations. Concerning safety, the highly-activated and contaminated components have an impact on the flexibility of the facility. In case of residual radioactivity, the reduction of the individual and collective doses received by workers as well as the environmental impact is a considerable issue. The ALARA (As Low As Reasonable Achievable) principle must be respected during the maintenance interventions and the final disposal of radioactive waste, and demonstration is provided during the design of the facility. Components that could be activated and contaminated are adapted to ease the dismantling, handling and storage in order to minimize the radiation dose to workers (hands-on maintenance, use of glove box, remote tools and robotics).

FIELD QUALITY

Since the usual design of quadrupoles based on a truncated cylindrical hyperbola has been questioned [3] some investigations have been performed in order to study an optimized model capable of being manufactured and applied to radioactive and powerful beams.

Quadrupole model

Several pole shapes of electrode have been considered for this study based on circular and hyperbolic forms with sharp or soft edges. The following well known equation was used to draw the basic hyperbola shape:

$$\left(\frac{y}{a}\right)^2 - \left(\frac{x}{b}\right)^2 = 1 \quad (1)$$

The “a” parameter is constant and equal to 50 mm as it represents the half main-axis of the hyperbola so the aperture of the quadrupole. The “b” parameter defines the angle between the tangents to the hyperbola and is equal to a for a 90° angle, which is our case with a 4-fold symmetry quadrupole shape.

The circular pole with a radius of R = 57.25 mm equal to 1.145 times the aperture radius [4] was compared to the hyperbolic poles defined by equation (1). The radial field showed to be the most linear for the case of the hyperbola (a; b) = (50; 50). Table 1 presents the different parameters of the electrodes.

The electrostatic fields were computed using IES Lorentz 2D/3D [5]. The meshing used to solve the model is quadratic and its refinement is so-called self-adaptive. Neumann and Dirichlet boundary conditions are applied in z and x/y respectively (i.e. the poles are surrounded by a grounded plate). In parallel to these simulations, the model of quadrupole was also computed using the code OPERA [6]. This latter allowed an optimization of the shape of the quadrupole electrodes by varying several parameters and by modifying the geometry at the edges of the poles.

Table 1: Parameters of the quadrupole

Parameter	Value
Pole length (mm)	200
Hyperbola coefficients (a; b) (mm)	50; 50
Aperture diameter (mm)	100
Voltage on the electrodes (kV)	± 3

Field maps

The distribution of the voltage is presented in Fig. 1. The field modulus on a circle of 40 mm radius in the centre of the quadrupole presents a better homogeneity for hyperbolic shapes, see Fig. 2.

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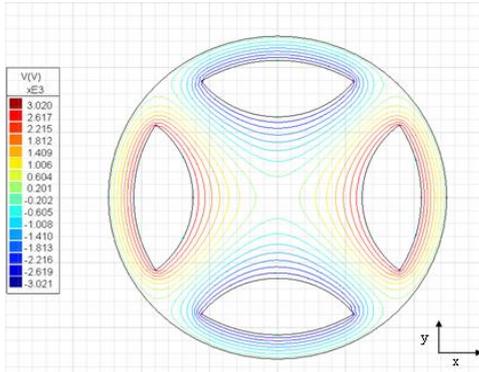


Figure 1: Potential distribution between electrodes.

The study of the components of the transverse electric field in the centre of the quadrupole shows a linearity of the field. Due to the relatively long electrodes and reasonably small aperture the effect of the grounded surrounding parts is small.

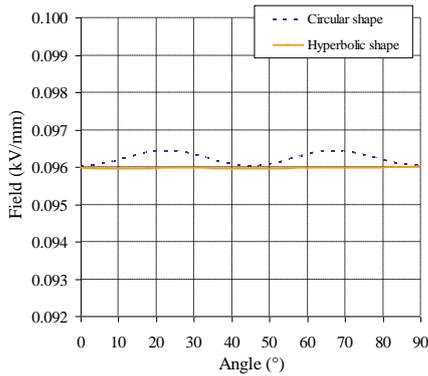


Figure 2: Field modulus on a circle of 40 mm radius versus the angle. $R=57.25$ mm and $(a; b)=(50; 50)$.

The fringe fields are determined for the standard electrode shapes and compared with the optimized one, see Fig. 4. These optimized shapes are obtained by iteration on the dimensions of the hyperbola and the cut provided on the surface with the help of an OPERA3D tool, see Fig. 3. The effective length of the quadrupoles and the distance for which the field can be considered as negligible (i.e. $E_z \sim 10^{-3}$ of the nominal value) are determined. The fringe field extension is ≈ 300 mm and the focusing distance is ≈ 1174 mm from the quad center.

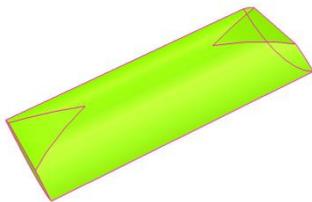


Figure 3: Drawing of a single electrode after optimization of the cut on both sharp edges.

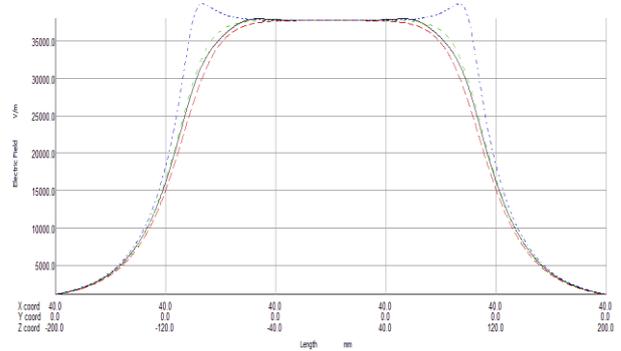


Figure 4: Longitudinal electric field for the initial (with horns) and after several steps optimized electrode shapes.

Harmonic analysis

The electric field is decomposed with a Fourier series expansion. The first harmonic corresponds to a pure dipole component, the second harmonic to a pure quadrupole component, etc. Due to symmetries in real optical elements, only a few harmonics should appear in the field decomposition. For a symmetric 4-pole arrangement (2nd order harmonics), the main higher order components are odd multiples: 6th order (also called dodecapole), 10th order and 14th order.

An optimization procedure has been developed inside the OPERA3D code to minimize the higher-order components that contribute to the total field. The harmonics are evaluated at a radius $r = 40$ mm, which corresponds to 80% of the quadrupole aperture. The two edges of the quadrupole are cut by an elliptical cylinder, with 3 shape parameters that are used for the optimization iterations, see Fig. 3. These are the ellipse long axis length a , the ellipse short axis length b and the distance Z_0 of the ellipse center from the quadrupole center. The best optimization result was obtained for $a = 25.89$, $b = 116.72$ and $Z_0 = 86.61$ mm. Table 2 shows the results obtained with and without edge shape optimization. The optimized edges model case manages to reduce the overall contribution of the higher order harmonics by one order of magnitude. Nevertheless improvement obtained for one term lead to degradation of other ones compared to the sharp edges model case but their sum will be smaller.

Table 2: Harmonics values obtained for the two hyperbolic electrodes. The values A_n have arbitrary units.

n	Sharp edges		Optimized edges	
	A_n	A_n/A_2	A_n	A_n/A_2
2	9292	1	8973	1
6	47.26	5.09×10^{-3}	-0.11	1.20×10^{-5}
10	1.33	1.43×10^{-4}	-3.67	4.09×10^{-4}
14	0.28	2.98×10^{-5}	-0.38	4.23×10^{-5}

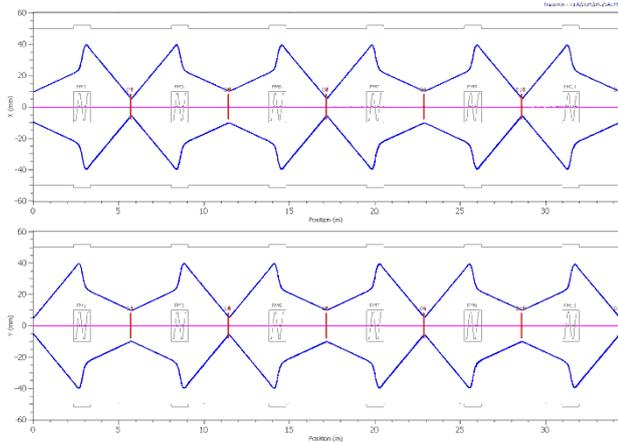


Figure 5: Horizontal (top) and vertical (bottom) beam envelopes at +/- 3 RMS in the beam line structure tested with different quadrupole models.

BEAM DYNAMICS

The results obtained by the electromagnetic code have been tested in a beam line structure simulated by the tracking code TraceWin [6]. Each quadrupole is simulated by a 3D field map, with a mesh size of 2 mm in all coordinates. The beam line is structured in quadrupole doublets with an inter-axis distance of 300 mm, two doublets forming a point-to-point unitary structure. To simulate a transport beam line of about 35 m, six doublets or twelve quadrupoles have been used and the envelopes in the transverse directions are shown in Fig. 5. The incoming beam is a $^{122}\text{Xe}^+$ beam at 60 keV with a Gaussian distribution (truncated at +/- 3 RMS) of 50,000 particles and a geometrical emittance of $80 \pi \cdot \text{mm} \cdot \text{mrad}$. The incoming RMS spot size is $(3.25 \times 1.75) \text{ mm}^2$.

The beam emittance distributions at the exit of the beam line are displayed in Fig. 6, for the hyperbolic shapes with sharp and optimized edges. In both cases the beam losses are not more than 1 %. The case with sharp edges exhibits a much stronger tail effect (S-shaped cubic distortion) especially in the horizontal plane. The optimized shape edge model has a slightly better beam spot size at the exit of the beam line, $(3.29 \times 1.76) \text{ mm}^2$ compared to the $(3.32 \times 1.77) \text{ mm}^2$ obtained with the sharp edge case. The improvement is not as good as expected from the harmonics calculations and further investigations are currently in progress.

The higher order multipole contributions are minimized at a radius of 40 mm, but outside this radius these contributions could lead to unexpected aberrations effects if a sizeable part of the beam is going through it. In further simulations the beam envelope could be reduced, to keep a margin compared to the 40 mm limit. As another improvement we will simulate and optimize directly a quadrupole doublet in the electromagnetic code.

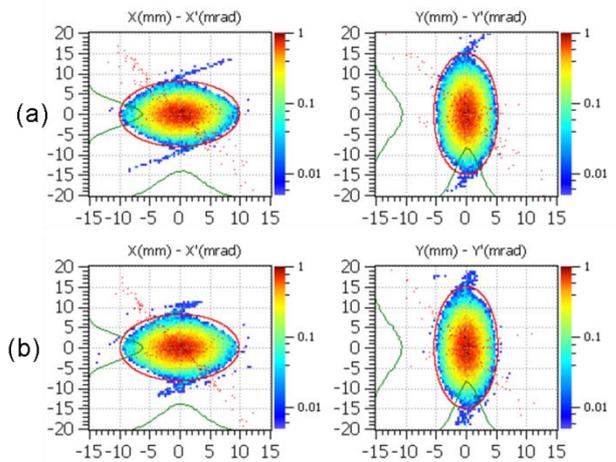


Figure 6: Horizontal (left) and vertical (right) beam emittance distributions at the exit of the tested beam line (after 12 quads); (a) for the sharp edges; (b) for the optimized edges of the hyperbolic electrode shapes.

CONCLUSION

The aim of the study is the reduction of the optical aberrations and the beam losses generated by the non-linear field region at the extremities of the electrodes of some electrostatic quadrupoles. A good compromise was reached between quad length, aperture, performances and costs with the help of different calculation codes and optimization procedures. A few investigations are required in order to consolidate the results and the nuclear engineering of the components before the manufacturing of a prototype expected in 2015.

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