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DEVELOPMENT OF SEPTUM QUADRUPOLE PROTOTYPE FOR DESY UPGRADING LUMINOSITY

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Abstract

Parker B., Smirnov N.L., Tkachenko L.M. Development of Septum Quadrupole Prototype for DESY Upgrading Luminosity: IHEP Preprint 98-55. – Protvino, 1998. – p. 9, figs. 5, tables 4, refs.: 3.

In the frames of collaboration between IHEP and DESY the prototype of the septum quadrupole based on existing in DESY QC quadrupole has been developed, manufactured and tested in IHEP. The main goal of this R&D was to choose a magnet configuration including a septum plate, a septum notch for the electron beam and trim-coils matching to specify and further apply in a full-scale magnet. The ingenious magnetic correcting system allowing one to get a high field quality of a few units 10^{-4} inside the operating range of the proton beam has been suggested. A chosen optimal geometry of the reflecting iron plate provides a required field magnitude along the electron beam path as well. The computer simulation of various geometric distortions influencing on the field quality has been performed and, as a result, the tolerances to the production accuracy have been formulated. These analyses displayed very strict requirements to both the manufacturing accuracy and magnetic properties of the septum plate steel.

Аннотация

Паркер Б., Смирнов Н.Л., Ткаченко Л.М. Разработка прототипа септум квадрупольного магнита для повышения светимости ускорителя в DESY: Препринт ИФВЭ 98-55. – Протвино, 1998. – 9 с., 5 рис., 4 табл., библиогр.: 3.

В рамках сотрудничества между ИФВЭ и DESY в ИФВЭ разработан, изготовлен и испытан прототип септум квадрупольного магнита, основанный на существующем в DESY QC квадруполе. Основная цель разработок заключалась в выборе и оптимизации геометрии магнита, включая септум пластину, вырез в ней для электронного пучка и систему корректирующих катушек. Результаты этих исследований будут использованы при разработке полномасштабного магнита. Была предложена оригинальная система коррекции магнитного поля, позволяющая получить высокое качество поля в несколько единиц 10^{-4} на всех уровнях тока и во всей рабочей области протонного пучка. Выбранная оптимальная геометрия отражающей пластины магнитного ярма обеспечивает требуемый уровень поля в области электронного пучка. Проведено компьютерное моделирование различных искажений геометрии, влияющих на качество поля, в результате были сформулированы допуски на точность изготовления. Эти анализы показали жесткие требования как к точности изготовления, так и к качеству магнитных свойств материала септум пластины.

1. Introduction

The program of the luminosity upgrade at the HERA electron-proton accelerator has been developed in DESY and this program is now found at the stage of accomplishment. According to this program the magnetic structure in the interactive region will be replaced.

In the frames of collaboration between IHEP and DESY the prototype of the septum quadrupole based on the existing QC quadrupole in DESY has been developed, manufactured and tested in IHEP in order to determine, investigate and predict various magnetic characteristics which can present in a full-scale magnet.

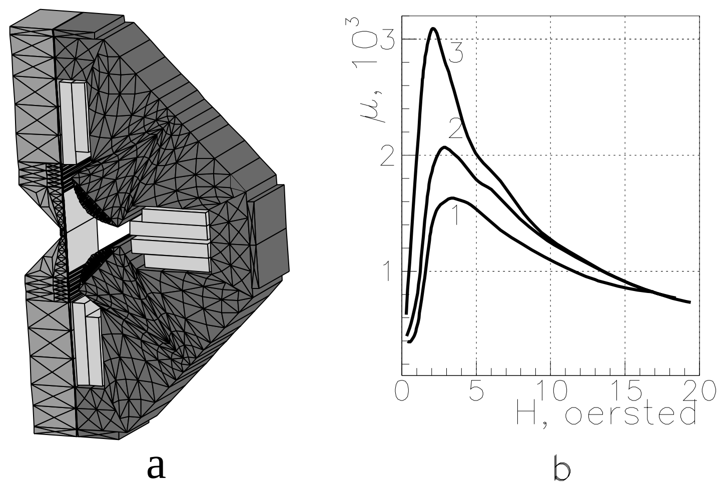

Fig. 1. Cross-section of the septum quadrupole (a) and magnetic properties of CT10 steel quality (b).

A general view of the top half of the septum quadrupole is shown on Fig.1a, where the left half of the quadrupole is replaced by the reflecting septum plate of 70 mm width. The aperture of the proton beam is situated inside of the magnet aperture and the beam centre is shifted in the horizontal direction to the right from the septum plate by 17 mm. The sum of modules of the lower field nonlinearities on the reference radius of 15 mm with the circle centre coinciding with the centre of the proton beam must not exceed 5×10^{-4}

at all levels of operating current $I_0/8 \le I \le I_0, I_0 = 380$ A is the maximal turn current. The aperture of the electron beam is placed in the notch of the reflecting plate, where the external field must be less than 5 G and the distance between the nearest edges of the proton and electron vacuum chambers must be no more than 18 mm.

2. Optimization of reflecting plate geometry

Geometry optimization of the reflecting plate was carried out using the MULTIC code[1].

Magnetic properties of the iron septum plate are shown on Fig.1b, where curve 1 is the magnetic permeability for the sample which was cut from the plate before annealing, curve 3 belongs to the sample which was annealed. The sample for curve 2 was cut from the plate after annealing and mechanical working. One can see that the annealing increases maximum magnetic permeability about by a factor two, but a mechanical working decreases the one by $\sim 30\%$. All the further calculations have been made using curve 2.

The field in the aperture can be presented as a series

$$B_{\mathrm{y}} + \mathrm{i}B_{\mathrm{x}} = B_0 \sum_{n=1}^{\infty} W_{\mathrm{n}} \left(\frac{x + \mathrm{i}y}{r_0} \right)^{\mathrm{n}-1}, \tag{1}$$

where $B_0 = G_0 r_0$, G_0 is the field gradient, r_0 is the reference radius, $W_{\mathrm{n}} = b_{\mathrm{n}} + \mathrm{i}a_{\mathrm{n}}$ are the nonlinearities of $\mathrm{n} - 1$ order.

In the intact quadrupole the calculated field gradient equals 16.05 T/m at the maximal turn current $I_0 = 380$ A and all the allowed field nonlinearities like $b_{4\mathrm{n}-2}$ are less than 1×10^{-4} on a reference radius of 25 mm. All the nonlinearities of type b_{n} appear on a shifted circle to the right along the horizontal axis. The lower field nonlinearities on a circle with a reference radius of 25 mm and a shifted centre by 30 mm are presented in Table 1 for the symmetrical quadrupole and the quadrupole with the reflecting septum plate without a notch. The measured nonlinearities under the same conditions are shown in the last line for a comparision.

Table 1. The calculated field nonlinearities, 10^{-4}; 1 — intact quadrupole, 2 — MSQ quadrupole with reflecting plate without notch (* — measured nonlinearities).

n	3	4	5	6	7	8	9	10
1	1.2	0.3	-0.7	-0.8	-0.3	-0.0	-0.3	-0.4
2	2.6	0.2	-0.7	-0.8	-0.3	-0.2	-0.3	-0.4
2*	2.2	0.5	-0.5	-0.1	-0.1	-0.2	-0.4	-0.4

It is convenient to introduce a function [2] in order to define the influence of the reflecting plate on the field quality in the cross-section:

$$f(r) = f(x = y) = \frac{G_{\mathrm{x}}(x = 0, y)}{G_{\mathrm{y}}(x, y = 0)} - 1, \tag{2}$$

Obviously, $f(r) \equiv 0$ for all r in the symmetrical quadrupole.

The notch with zero partition width in the plate distorts the field quality in the aperture very strongly as the magnetic flux cannot been closed with a yoke. For example, the cut with 45° angle counted from the median plane gives the magnitude of f(r=10cm) equal to about 10%.

The partition with a width of w in the septum plate allows the magnetic flux to pass through the yoke and improves essentially the field quality in the aperture. The dependence of the maximal values of function $f(r)$ at the maximal quadrupole main current versus w is presented on Fig.2a. One can see that the function $f_{\max}(w)$ has the sharply defined minimum at the width of the partition of about 5 mm and equals approximately 4.5×10^{-4}.

The external field does not exceed 3 G in the notch and its maximal value is outside the electron beam aperture (Fig.2b).

The magnet geometry with 5 mm wall width gives a high field quality at the maximal quadrupole current I_0. However, the field quality deteriorates at lower current levels. For example, the maximal value of function $f(r)$ exceeds the magnitude of 6×10^{-3} at the quadrupole current $I = I_0/8$.

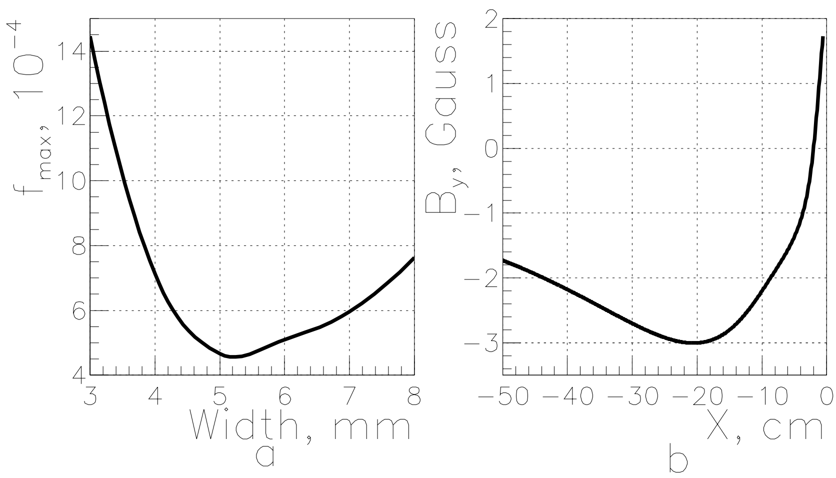

Fig. 2. The dependence of the maximal values of $f_{\max}(r)$ versus the partition width (a) and the distribition of the external field along the horizontal axis of the quadrupole (b).

3. Correcting trim-coils

To adjust the field quality at all current levels, we inserted a trim-coil with dimensions 3×3 mm^2 inside a groove of the partition. Here and further on we will regard the top half of the MSQ magnet supposing the symmetrical reflection in the bottom half with the same currents. We kept a sum of wall width $w = w_1 + w_2$ equal to the optimal width of 5 mm without the trim-coil. Here w_1 is the interior wall width of the partition from the side of the proton beam and w_2 is the exterior wall width from the side of the electron beam. This geometry with zero current in the trim-coil gives the maximal magnitudes of function $f_{\max}(i, w_1)$ in the intervals $w_1 \in [2, 4]$ mm, $\hat{\imath} = I/I_0 \in [1/8, 1]$, which can be described by the formula

$$f_{max}(\hat{\imath}, w_1) = [\alpha(\hat{\imath}) + \beta(\hat{\imath}) w_1] \times 10^{-4} \tag{3}$$
$$\alpha(\hat{\imath}) = 147 - 246\hat{\imath} + 114\hat{\imath}^2, \quad \beta(\hat{\imath}) = -17 + 24\hat{\imath} - 9\hat{\imath}^2,$$

Formula (3) shows that the $f_{\max}(i, w_1)$ has a slight slope against w_1, but increases sharply at the small fields.

A small current i_1 in the trim-coil can change the sign of $f(r)$ quite easily at a high level of the field as it is shown on Fig.3a. Permissible limits of the $f(r)$ change are marked by the horizontal lines. Hence, we can set up the function of $f(r)$ in the given limits by a suitable choice of the i_1 current. However, it is impossible to suppress this function in the given limits at the lower level field. Fig.3b shows that even 30 A correcting current in the trim-coil does not allow one to do this. One can see that the function has an acute maximum in the vicinity of the trim-coil and the total level looks like plateau with a value of about $2.5{\times}10^{-3}$ in the whole region. The trim-coil influences only the maximum but it has no effect on the total level.

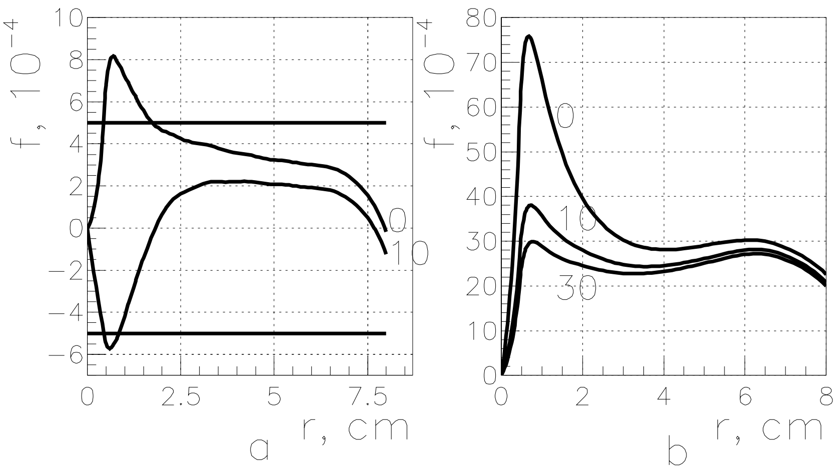

Fig. 3. The dependences of $f(r)$ for two current values (in A) of the trim-coil at the maximal field (a) and for various trim-coil currents at the lower main current $I = I_0/8$ (b).

To reduce the total level of the function $f(r)$ we inserted the second trim-coil adjoing the reflecting plate inside the aperture of the proton beam. This coil has to have a shape of a narrow and stretching rectangle. A height of the flat coil must overlap the whole working range of the aperture. Since there are rigid requirements to the placement of the vacuum chamber of proton beam, this trim-coil must have small enough width as far as it is possible to manufacture it. In fact, one can make its width less than 1 mm.

The behaviors of the functions $f(r)$ for various values of the flat coil height in cm are shown on Fig.4a at the currents $I = I_0/8, i_1 = i_2 = 10$ A, where i_2 is the current in the second trim-coil. The height of the flat coil is chosen equal to 6 cm in order to reduce currents in both the trim-coils. The shapes of function $f(r)$ are shown on Fig.4b at the chosen dimensions of the flat coil for various values of trim-coil currents equal in both the correcting coils at the main quadrupole current $I = I_0/8$. It follows from Fig.4b that the function $f(r)$ is completely found in the given limits at the current in both the trim-coils $i_1 = i_2 = 6$ A.

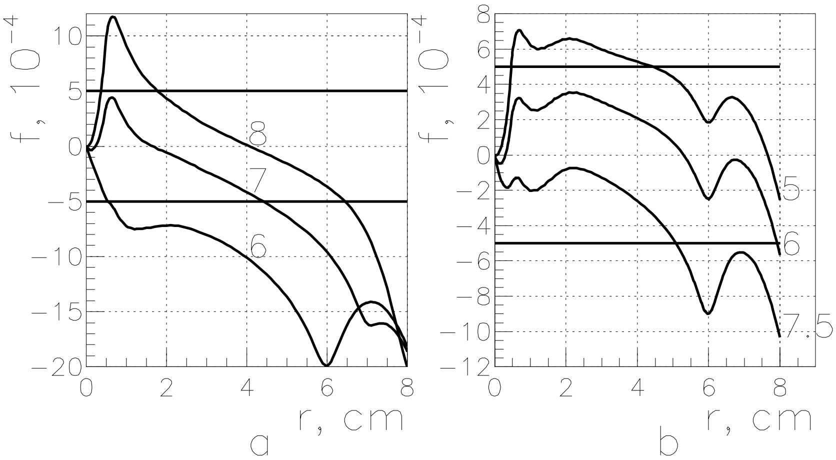

Fig. 4. The dependences of the function $f(r)$ for various heights of the flat trim-coil in cm (a) and for various trim-coil currents in A (b).

The lower end of flat trim-coil must be in the medium plane without any gaps. Attempts to cut this flat coil from below give a very strong distortion of field quality that cannot be improved by correcting currents.

4. Analysis of field distortion and tolerances of manufacturing accuracy

The optimized geometry of the MSQ quadrupole allows one to get a high field quality at all the levels of main coil current under ideal production. The manufacturing errors are inevitable during the process of production. As it follows from (3), the field distortions increase at lower currents of magnet, therefore, all further calculations have been carried out at the quadrupole current $I = I_0/8$.

The influence of the manufacturing errors on the field quality is illustrated by Fig.5a. All the results are presented at the optimal currents of the correcting coils $i_1 = i_2 =6$ A for the ideal geometry. The lower curve belongs to the ideal geometry and also to geometries with various distortions of the flat correcting coil. The following distortions of this coil have been considered:

- the parallel displacement of the coil to the right from the septum plate by 0.5 mm,
- the coil skewness, the displacement of its lower or upper part to the right from the septum plate by 0.5 mm;
- the increase of coil width by 0.5 mm.

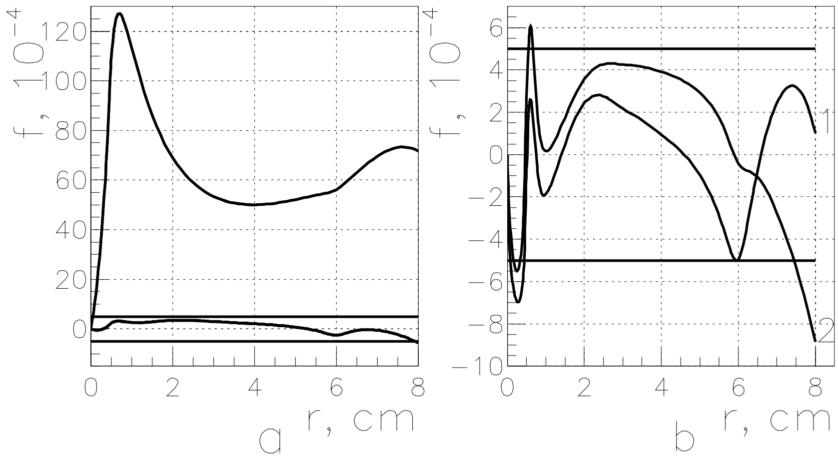

Fig. 5. The dependence of function $f(r)$ for various geometric distortions (a) and for geometries with shift of septum plate on -20 μm (1) and $+20$ μm (2) and optimal current values in correcting coils.

One can see from this picture that any distortions of the flat coil have no influence on the field quality in the aperture, all the curves coincide completely. Thus, the tolerances on the manufacturing accuracy of the flat coil are totally free. Obviously, the geometrical distortions of the notch correcting coil have also no influence on the field quality, which is also confirmed by the calculations, because its contribution to the field is defined only by the influence of its current on the distribution of a magnetic flux in iron.

The upper curve illustrates the behaviour of function $f(r)$ in case of the displacement of the septum plate to the left from the quadrupole by 0.1 mm. For this displaced plate we have also considered two positions of the flat correcting coil: the initial position and the shifted coil together with the septum plate. As is expected, the curve $f(r)$ is independent against the position of the flat coil either, however, we have very strong influence of geometric distortions of the septum plate on the field quality in the aperture.

Real manufacturing accuracy can be no worse than 20 μm. Nevertheless, even at such distortion of the septum plate it is impossible to obtain a satisfactory field quality. Calculations show that a small notch coil works extremely ineffectively, because the width $w_1 = 3$ mm is large enough to change a magnetic flux by the small current of the notch coil. Of course, it is possible to get a good field quality by large enough current in this coil, but it is extremely undesirable.

After the completion of the calculation cycle it has been found that it is more efficient to decrease the width w_1 to 2 mm and simultaneously to increase the width of the second wall to 3 mm, keeping the optimal value of 5 mm of the total width. It is easy enough to suppress the field distortion for such geometry with small currents in the correcting coils when the plate is shifted to the left ($-$) or to the right ($+$) by 20 μm (Fig.5b). Curve 1 corresponds to the geometry with -20 μm shift of the plate and correcting trim-currents 5 A in the notch coil and 9 A in the flat coil. These values for curve 2 are $+20$ μm, 1 A and 3 A, accordingly.

5. Analysis of distortions of field nonlinearities

It is practically impossible to measure function $f(r)$ by the magnetic measurements. It is more convenient to evaluate the field quality on its harmonic analysis. The magnitudes of the correcting currents for two levels of the main field and three positions of the septum plate Δ_f are presented in Table 2 as well as the corresponding field nonlinearities in units of 10^{-4} defined on a reference radius of 15 mm with shifted circle centre to the right by 17 mm along the horizontal axis. The plate shift is shown in Table 2 in the first column. The sign "+" means the right shift and "−" is the left shift, both are by 20 μm. Note that the correcting current was roughly selected. It is more convenient and simpler to find a more exact set for each particular geometry experimentally.

Table 2. Field nonlinearities of MSQ quadrupole, 10^{-4}, $r_0 = 15$ mm, $x_c = 17$ mm.

Δ_f, μm	i_1, A	i_2, A	3	4	5	6	7	8	9	10
					I = $I_0/8$					
−20	5	10	1.5	0.6	0.0	0.1	0.0	0.0	-0.2	0.2
0	3	6	1.5	0.9	-0.1	0.1	-0.1	0.1	-0.2	0.2
+20	2	3	2.1	0.6	0.2	-0.1	0.1	0.0	-0.1	0.2
					I = I_0					
−20	1.5	9	-0.0	0.5	-0.4	0.2	-0.2	0.2	-0.3	0.3
0	0.5	5	0.3	-0.2	0.0	-0.0	-0.1	0.2	-0.3	0.2
+20	1	3	-0.7	-0.0	-0.1	0.1	-0.2	0.1	-0.3	0.3

Surely, the nonlinearities are essentially large on the circle with the shifted center along the horizontal axis by 30 mm and reference radius 25 mm. Magnetic measurements have been performed on this circle. Higher correcting currents in both the trim-coils equal to 6 A and 15 A for +20 μm shift as well as 15 A and 20 A for −20 μm shift of the reflecting plate are needed.

Magnetic properties of steel have a strong influence on the field quality. For example, the field nonlinearities with $r_0 = 25$ mm and $x_c = 30$ mm are presented in Table 3 for two levels of the main current and zero correcting currents for the steel with the annealing and mechanical working (curve 2, Fig.1b, "2" in Table 3) and without annealing (curve 1, Fig.1b, "1" in Table 3).

Table 3. Nonlinearities of MSQ quadrupole, 10^{-4}, with annealing and mechanical working (2) and without annealing (1) of the reflecting plate, $r_0 = 15$ mm, $x_c = 17$ mm.

I	Steel	3	4	5	6	7	8	9	10
$I_0/8$	2	13.2	1.1	1.0	-0.9	0.9	-0.3	0.1	-0.7
$I_0/8$	1	17.5	-1.0	1.9	-1.7	1.6	-0.8	0.5	-0.9
I_0	2	-0.1	-2.5	-2.4	-2.1	-1.2	-1.0	-0.8	-0.6
I_0	1	16.2	9.2	4.8	-7.0	4.0	-4.0	2.5	-2.8

Table 3 and Fig.1b show that the maximal permeability of the steel must be no less than 2500.

An air gap in the back iron wall of the septum plate, connecting the region of electron beam and the notch coil, is inadmissible. This gap deteriorates nonlinearities in the aperture of proton beam very strongly. Magnetic characteristics of steel have also a great influence on the field quality. The nonlinearities on the circle with parameters $x_c = 30$ mm and $r_0 = 25$ mm depend on the value of gap Δl which can be described as

$$b_n(\Delta l) = (u_n + v_n\sqrt{\Delta l}) \times 10^{-4}, \tag{4}$$

where Δl is in mm.

The coefficients u_n and v_n are presented in Table 4 for the steels before annealing and after that at the maximal quadrupole current. The external field in the region of electron beam also sharply rises against the gap value and the maximal magnitude B_{max} is placed near the point $x = -10$ mm. B_{max} can be as well described by the formula

$$B_{max}(\Delta l) = u_B + v_B\sqrt{\Delta l}. \tag{5}$$

Here Δl is also in mm and B_{max} is in G. The coefficients u_B and v_B for B_{max} are presented in Table 4 in the last column.

Table 4. Influence of the air gap on the field quality.

n	3	4	5	6	7	8	9	10	B_{max}
Reflecting plate before annealing									
u	5.5	-4.5	0.0	-3.3	0.5	-1.7	0.2	-1.2	11.8
v	30.8	-19.2	15.2	-13.4	10.6	-8.4	6.7	-5.4	70.2
Reflecting plate after annealing									
u	3.2	-3.4	-0.8	-2.6	-0.1	-1.3	-0.2	-0.9	8.1
v	11.2	-6.9	5.4	-4.7	3.7	-2.9	2.3	-1.8	25.9

Conclusion

The results of developments and investigations of the septum quadrupole prototype defined the design of a full-scale magnet for its utilization in the interaction regions of HERA. The prototype would also be useful for improving the transfer efficiency of protons from PETRA to HERA via the existing PR-Weg transfer beamline [3]. With a MSQ placed close to the existing proton injection septum in HERA, it would be possible to reduce the magnitude of β-peaks near the end of the PR-Weg by as much as 45% and thereby derive a 25% effective increase in the available aperture under critical locations.

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