Simulation and Design of the Permanent Magnet Multipole for DC140 Cyclotron

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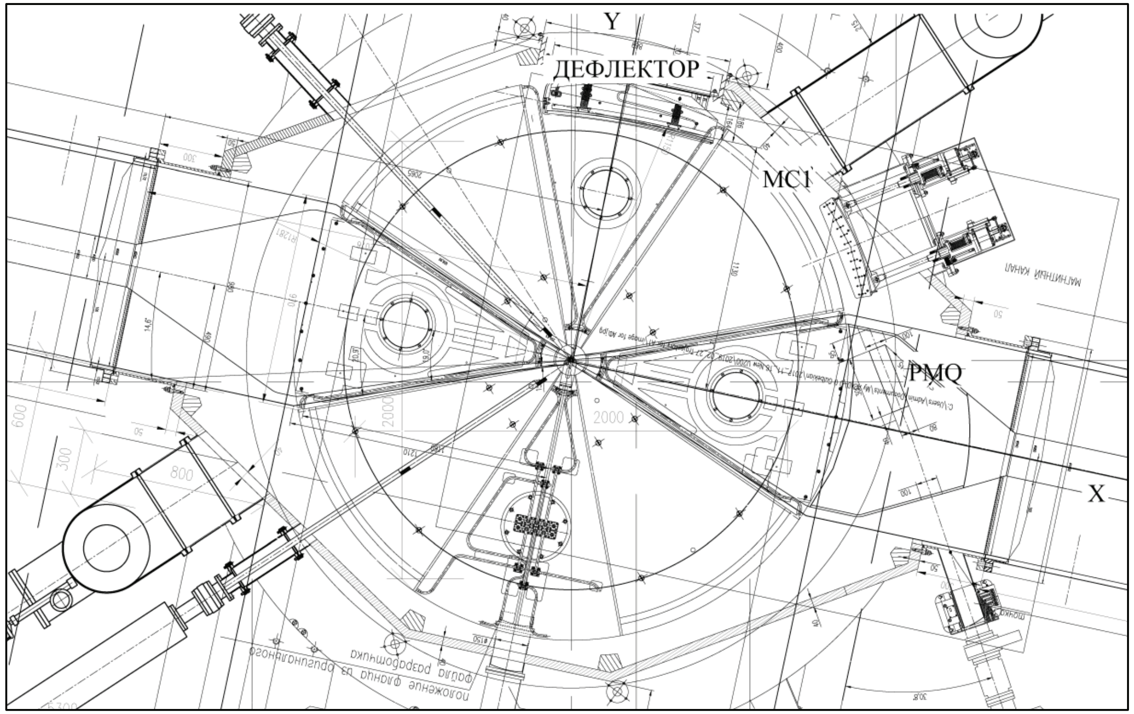
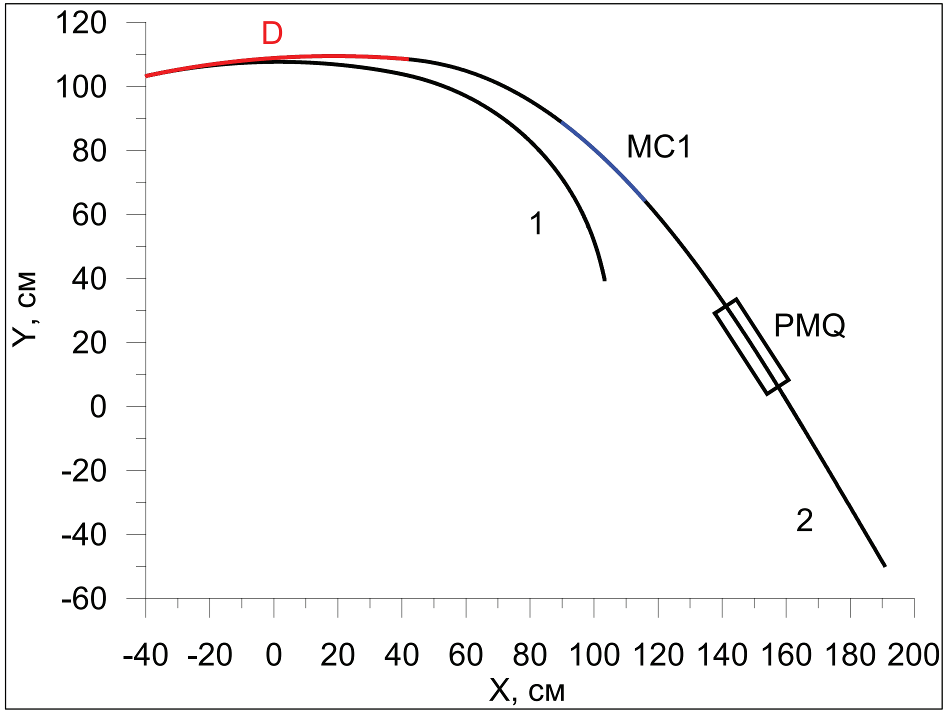
Cyclotron DC140

Working region in DC140



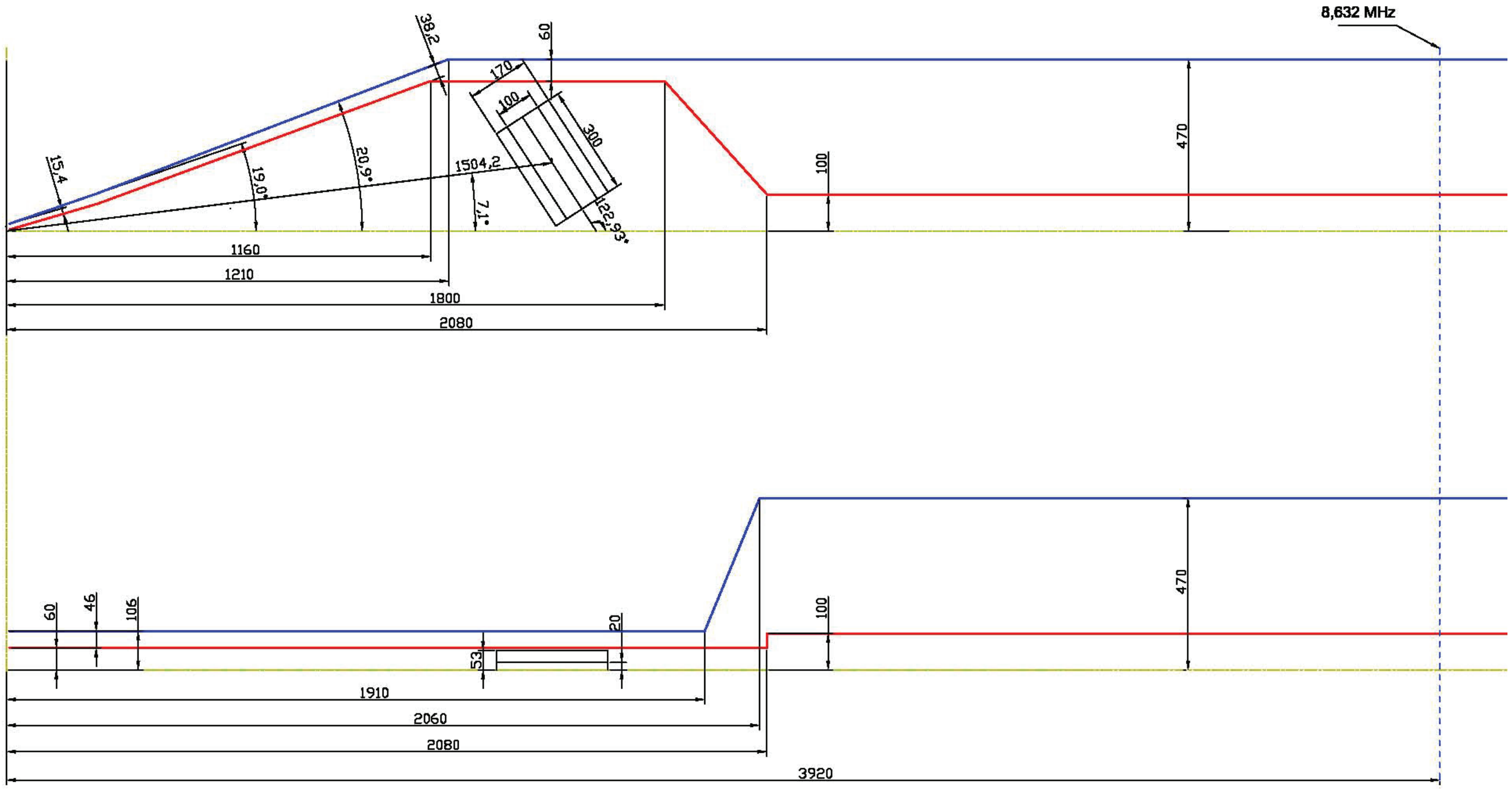
DC140 beam extraction scheme



D – electrostatic deflector
MC1 – passive magnetic channel
PMQ – PM quad

1 – closed orbit
2 – extraction orbit

PMQ arrangement with DC140 dees



Required PMQ parameters

Field gradient (G_0)	8.1 T/m
Working region (hor. × vert.)	64 mm × 25 mm
Aperture (hor. × vert.)	80 mm × 32 mm
Overall sizes (hor. × vert.)	170 mm × 106 mm
Effective lenght* (L_{eff0})	299.26 mm
Error in working region** ($\Delta_{x,y}$)	±1%

*The effective length:

$$L_{eff\,0} = \frac{1}{G_0} \int_{-L/2}^{L/2} \frac{\partial B_y(0,0,z(s))}{\partial x} dz(s)$$

**A linear approximation error in the horizontal and vertical directions:

$$L_{eff\,0}\Delta_x = \frac{1}{G_0 x} \int_{-L/2}^{L/2} \left[B_y(x,y,z) - \frac{\partial B_y(0,0,z)}{\partial x} x \right] dz = L_{effx} - L_{eff\,0}$$

$$L_{eff\,0}\Delta_y = \frac{1}{G_0 y} \int_{-L/2}^{L/2} \left[B_x(x,y,z) - \frac{\partial B_x(0,0,z)}{\partial y} y \right] dz = L_{effy} - L_{eff\,0}$$

PMQ operating conditions

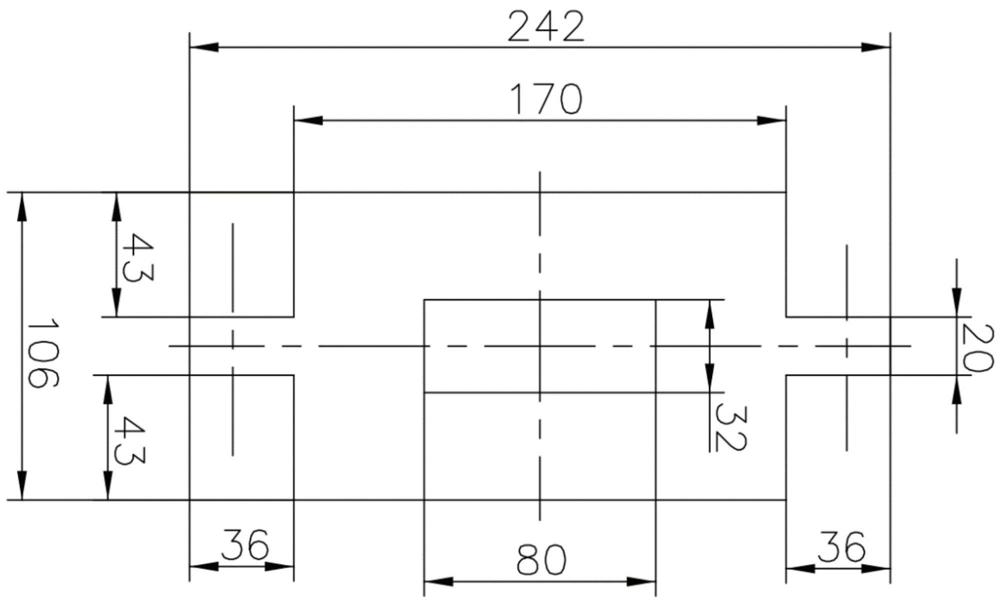
External field	0.35 T
Vacuum	10^{-7} Torr
Operating temperature	30-40 °C
Temperature range	20-70 °C
Life time	10-15 years

PMQ structure

The DC140 quad will be designed as a set of identical PMs rigidly fixed in a non-magnetic housing encircling the aperture.

Additional aspects of the quad specification

- simple PM shape, preferably cuboidal bricks,
- minimized number of PM in assembly,
- minimized nomenclature,
- commercial availability of PM.



Stages of PMQ design

I .

The initial quad design is selected from an analytical study with the use of a simplified 2D model.
At this stage the number and positions of PMs are determined.

II .

Then the chosen configuration is optimized in iterative 2D and 3D parametric simulations with realistic PM shape and magnetic characteristics in mind. Simulated data are used to select candidate magnet materials, number, dimensions, and tolerated mechanical and magnetic errors of PM blocks.
As a result, the quad design is finalized, and an assembly procedure is proposed.

III .

Additional adjustment may be required on the basis of measurements of supplied PM.
The assembled quad is magnetically inspected to make sure the desired field requirements are reached.

Simplified 2D model of PMQ

Analytical model is based on the mathematically strict reasoning:

- If **M** = const, for 3D PM system of length L_{PM}:

$$\int_{-\infty}^{+\infty} \boldsymbol{B}_{3D}(x,y,z)\,dz = \boldsymbol{B}_{2D}(x,y)\cdot L_{PM}$$

- With distance, the field generated by an infinite PM of an arbitrary shape is approaching the field of an infinite PM cylinder with the same dipole magnetic moment.

- The field of a radially magnetized PM cylinder:

$$\boldsymbol{H} = \frac{(\boldsymbol{n},\boldsymbol{m})\boldsymbol{n} - \boldsymbol{m}/2}{\pi r^2}$$

$\boldsymbol{m} = \boldsymbol{M}\cdot \pi R^2$ – dipole magnetic moment per unit length;
$\boldsymbol{M}$ – magnetization vector, R – magnet radius;
$r = |\boldsymbol{r}|$ – distance between the magnet center and an observation point, $r > R$;
$\boldsymbol{r}$ – position vector to the observation point;
$\boldsymbol{n} = \boldsymbol{r}/r$ – unit vector from the magnet center to the observation point.

Field quality criteria

Field quality criteria is deduced from two assertions:

- Linear approximation errors in the horizontal and vertical directions, Δ_x and Δ_y, are below the field gradient error ε_G:

$$\left|\Delta_{x,y}\right| \leq \varepsilon_G = \frac{|\boldsymbol{G} - \boldsymbol{G}_0|}{|\boldsymbol{G}_0|}, \quad \boldsymbol{G} = \nabla B_y$$

- The beam in the magnet aperture is localized within a region of the elliptical shape.

Therefore, the field quality of the quad is assessed through the maximal deviation of the field gradient from the required level of 8.1 T/m within the ellipse inscribed in the 64 mm × 25 working region

PMQ optimization using simplified 2D model

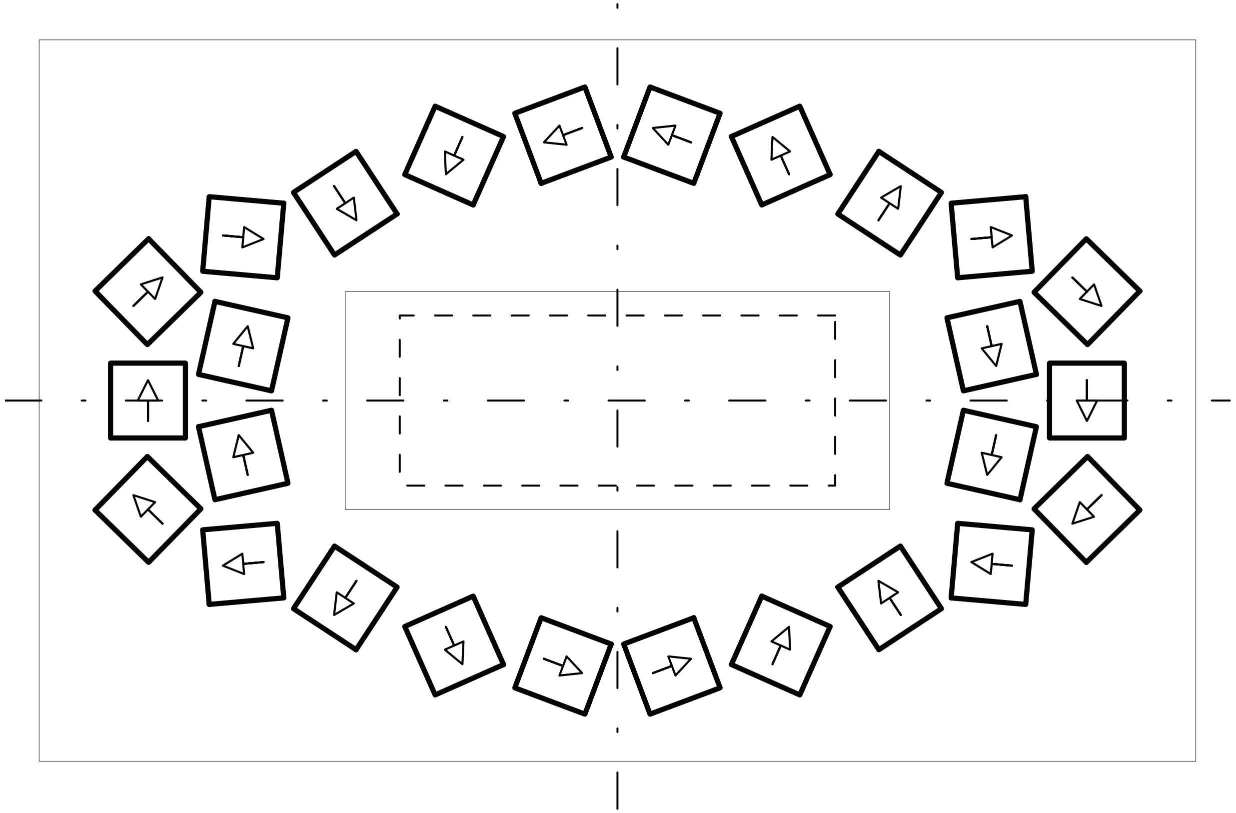
- PM rods are positioned over the XY plane around the aperture.
- Unknown components (m_x, m_y) of the dipole magnetic moments form the vector of unknowns X.
- Inside the working region a set of reference points is taken with a step $\Delta\phi = 1°$ over the line $x = a_x \cos\varphi$, $y = a_y \sin\varphi$, $0 \le \varphi \le \pi/2$, $a_x = 32$ mm, $a_y = 12.5$ mm.
- Target values of the field gradient $\mathbf{G}_0 = \nabla B_{0y} = (8.1, 0)$ T/m at the reference points create the right-hand vector Y_0.
- Values of field gradient at the reference points form vector Y = AX, where A is the matrix with coefficients derived from the field generated by a cylindrical magnet.

The optimal solution is searched through minimizing Φ at given Ψ :

$$\Phi = \max_k |\boldsymbol{m}_k|^2 = \max_k \left\|X^{(k)}\right\|_2^2$$

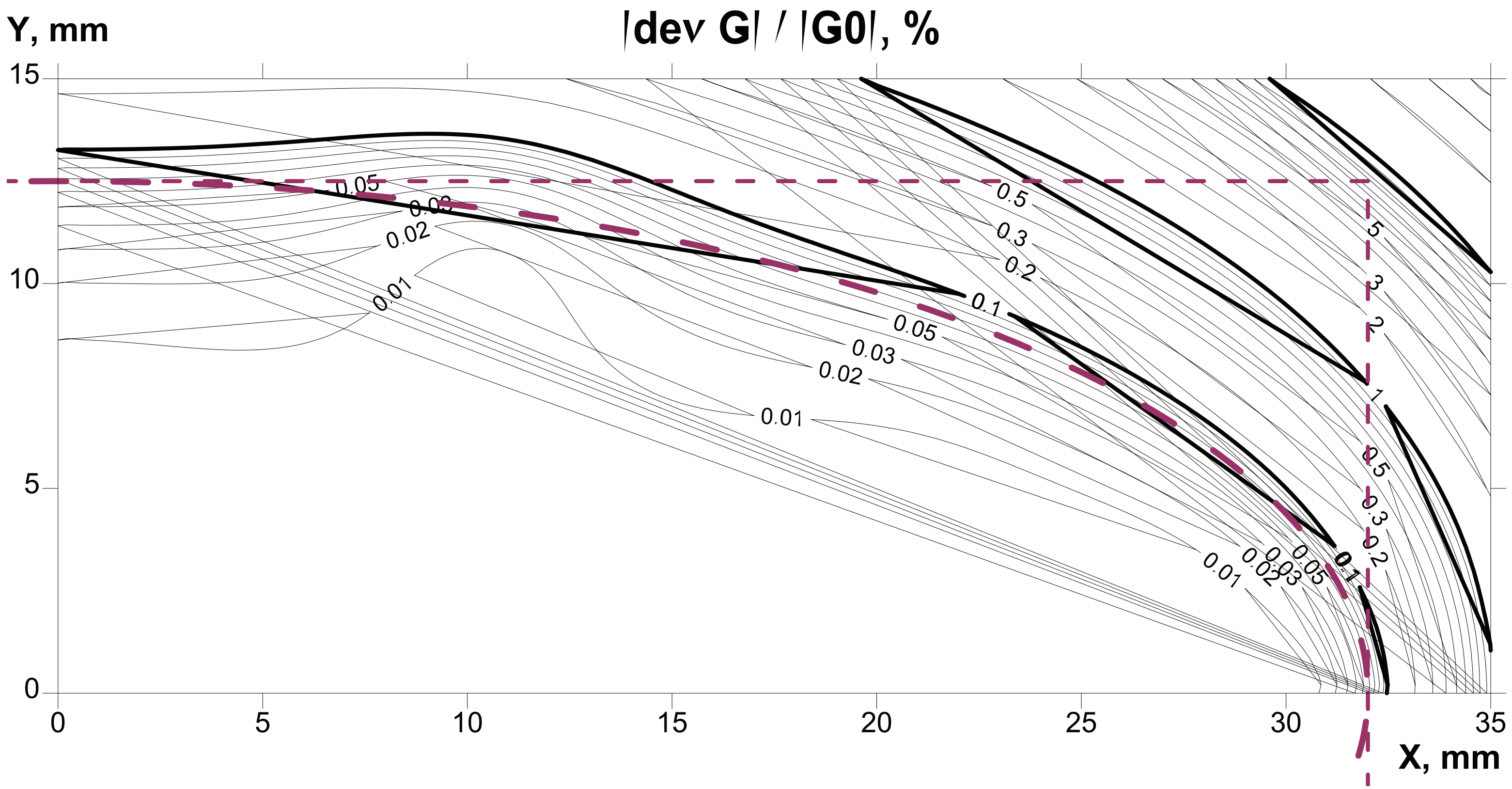
$$\Psi = \max_l |\boldsymbol{G}_l - \boldsymbol{G}_0|^2 = \max_l \left\|Y^{(l)} - Y_0^{(l)}\right\|_2^2 = \text{const}$$

Optimal solution on simplified 2D model



Quad formed with 26 identical 11 mm ×11 mm PM bricks each magnetized to 1.1402T.
Arrows indicate PM orientations,
dashed lines bound 64mm × 25mm working region,
solid lines are for 80mm × 32mm aperture and 170mm × 106mm overall sizes.

Relative gradient error in PMQ working region



Relative gradient error: $\varepsilon_G = |\delta \mathbf{G}|/|\mathbf{G}_0|$ (%).
Dashed lines indicate 64mm × 25mm working region with inscribed elliptical region.
Field gradient error in the elliptical region was found to be below 0.07%.

Perturbing factors influence on PMQ field quality

Perturbing factor	**max ε_G**
Unperturbed system	0.07%
Square PM cross-section	0.5%
Intrinsic PM degaussing ($\varkappa$=0.1)	5%
Mutual PM magnetization ($\varkappa$=0.1)	0.6%
Anisotropy $\varkappa$ ($\varkappa_{\|\|M}$=0.1, $\varkappa_{\perp M}$=0)	0.3%
3D representation ($\varkappa$=0.1)	0.17%

PMQ correction for disturbing factors compensation

At every iteration k (k = 0, 1, …):

- The target gradient value $\boldsymbol{G}_{targ}$ is prescribed at the reference points:

$$\boldsymbol{G}_{targ,k} = \boldsymbol{G}_0 - \Delta\boldsymbol{G}_{corr,k-1}$$

  (at k = 0: $\boldsymbol{G}_{targ,0} = \boldsymbol{G}_0$)

- Using $\boldsymbol{G}_{targ,k}$, optimization with the simplified 2D model is performed to determine:
  - orientation and magnetic moments for every PM: $\boldsymbol{m}_k$;
  - optimized gradient map: $\boldsymbol{G}_{simp,k}$.
- The obtained $\boldsymbol{m}_k$ are used in 2D or 3D simulation with perturbing factors involved. The simulated data represent expected gradient distribution: $\boldsymbol{G}_k$.
- Influence $\Delta\boldsymbol{G}_{corr,k}$ of the perturbing factors is estimated:

$$\Delta\boldsymbol{G}_{corr,k} = \boldsymbol{G}_k - \boldsymbol{G}_{simp,k}$$

It took 2 iterations to determine the PM parameters enabling the desired field quality accurate to

ε_G = 0.08%.

Optimized PMQ specification

PM parameters at operating temperature

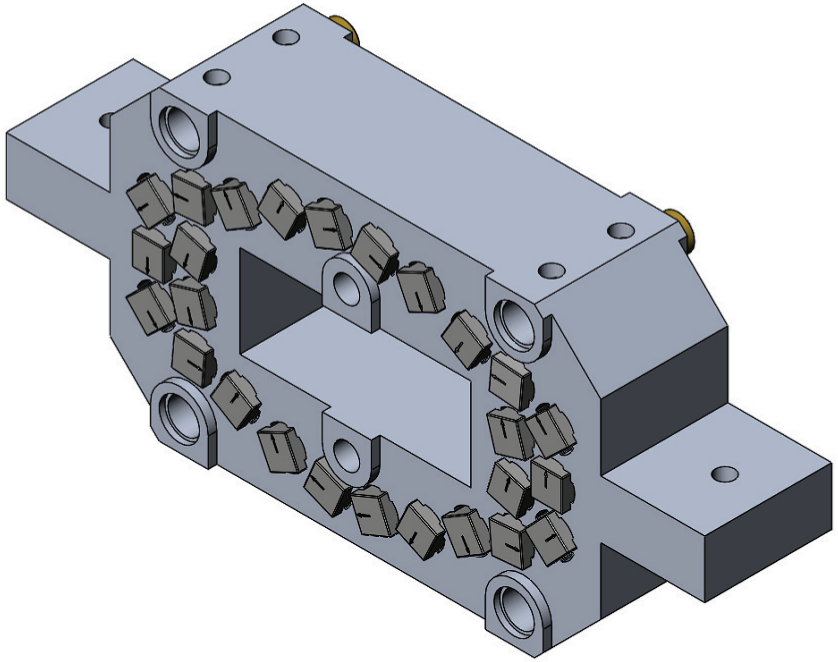
Remanent field B_r	1.1853 T
Magnetic susceptibility $\varkappa$	0.1
Linear piece of B-H curve	up to 1200 kA/m
Nd-Fe-B grade	N35SH, N35UH
PM cross-section	11 mm × 11 mm
PM length L_{PM}	300 mm
Total number of PM	26

Geometrical and magnetic tolerances

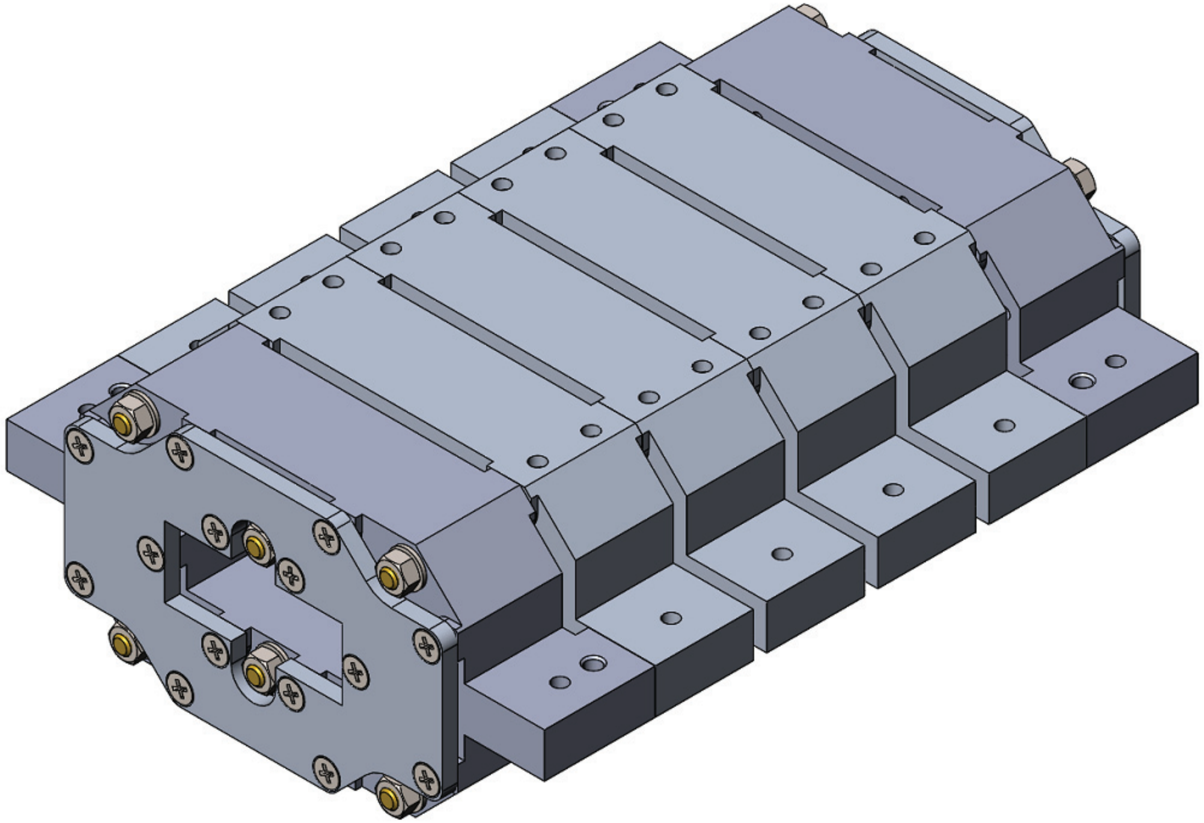
PM dimensions	± 0.05 mm
Remanent field $\|B_r\|$:	
- average over batch	± 3%
- single PM	± 1-1.5%
Magnetization direction in PM	± 1°
Positioning:	
- X, Y, Z coordinates	± 0.05 mm
- orientation	± 0.3°

Proposed PM quad design

PMQ segment



PMQ assembly



Thank you!