ISBN: 978-3-95450-215-8 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2022-TUPORI30

APPLICATION OF PERMANENT MAGNETS IN SOLENOID AND QUADRUPOLE FOCUSSING

J. D. Kaiser*[1], A.Ateş, H. Haehnel, U. Ratzinger, IAP, Goethe University, Frankfurt, Germany
[1]Helmholtz Research Academy Hesse for FAIR (HFHF), Frankfurt, Germany

Abstract

Permanent magnets can be used to design compact high gradient focusing elements for particle accelerators. Based on cheap industrial standard Neodym permanent magnets, design studies for Solenoids and Quadrupoles are presented.

The Solenoid design consists of three segments, where the outer segments possess a radial magnetization and the inner segments an axial magnetization. This increases the mean field strength in comparison to a singlet hollow cylinder solenoid.

The quadrupole design consists of 16 block magnets and is designed to be rather simplistic. The casing consists of two half shells, which can be easily mounted around a beam pipe. For a quadrupole triplet configuration the influence of different geometric parameters on beam transport regarding focusing strength and emittance growth is investigated.

Furthermore, a variation of the quadrupole design was mounted in vacuum in a triplet configuration. Using custom 3D-printed mounts for small raspberry pi cameras the beam could be observed inside the quadrupoles. A first prototype was constructed.

PERMANENT MANGETIC SOLENOIDS

In its simplest form, a permanent magnetic solenoid (PM-Solenoid) can be realized by a single axially magnetized hollow cylinder. A maximization of the coupling of the magnetic field across the aperture volume is crucial for the mean flux density along the beam axis. This is particularly weakened when the cylinder is lengthened. To counteract this, the solenoid is extended by two outer cylinder segments with a radial magnetization (Fig. 1).

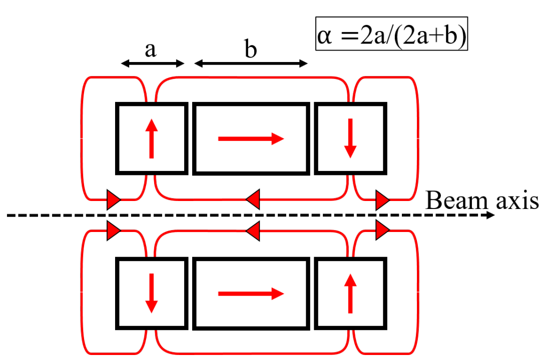


Figure 1: Cross-section of a PM solenoid consisting of three segments.

The ratio of the segment lengths α can be adjusted according to the geometrical parameters to a maxmimization of the mean flux density. For suitable parameter combinations, this can be increased by a factor of 2. Compared to a single hollow cylinder, the magnetic fields are concentrated in a smaller area as this changes direction between segments (Fig. 2). For an aperture radius of 20mm, the average magnetic flux density increases by 20% radially for both designs. This results in overfocusing only for the combined cylinders due to the concentrated field. This problem can be circumvented by reducing the illumination or designing the solenoid with smaller aperture radii.

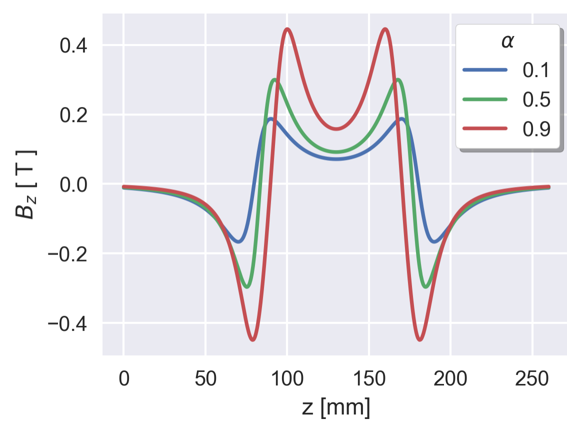


Figure 2: Field progression along the solenoid axis for three segment aspect ratios α.

For a cheap realization an arrangement of cuboid magnets can be derived, whose geometry is industrial standard and thus available at a low price compared to individually manufactured magnets (Fig. 3). The pole faces of the magnets, which correspond to the largest surface of the individual cuboids, are oriented according to Fig. 1. In this configuration, an average flux density of 0.5T can be achieved for an 80mm long solenoid and an aperture radius of 12mm with an outer radius of 32mm.

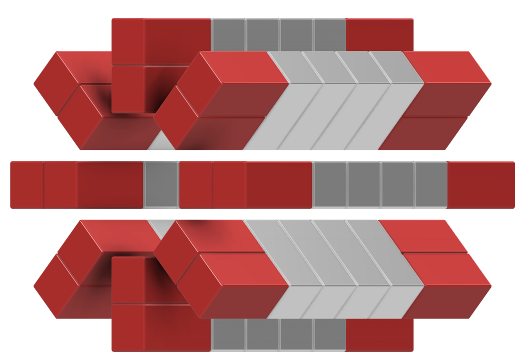


Figure 3: Arrangement of cuboid magnets to mimic the segmented PM solenoid.

* kaiser@iap.uni-frankfurt.de

ISBN: 978-3-95450-215-8 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2022-TUPORI30

PERMANENT MAGNETIC QUADRUPOLES

A permanent magnetic quadrupole (PMQ) can be realized in the simplest form from 8 cuboid magnets [1]. For the use of industrial standard magnets, the cuboids must have a square base, so that identical magnets can be used at all positions. This allows the magnets to be stacked, making higher gradients possible. The space existing between the main magnets can also be filled by additional magnets, see Fig. 4.

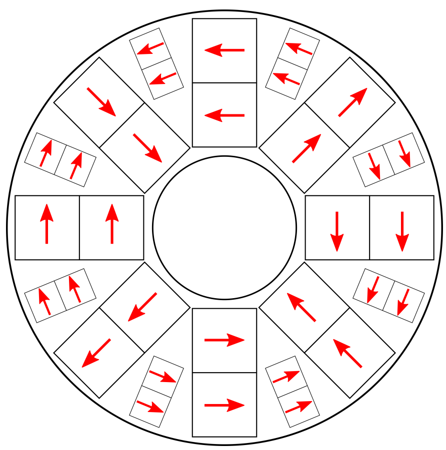


Figure 4: Arrangement of cuboid magnets with a square base to form a PMQ.

For flexible use and easy handling, a magnetic holder was developed which is clamped around a beam pipe (Fig. 5). This consists of two half-shells and fully encloses all individual magnets, so that they are firmly installed at all times during installation and removal. For use in combination with several PMQ, drill holes are provided with which a cover can be attached. Especially short magnets (20mm) come off easily. It is manufactured via 3D printing and first prototypes made of plastic (PLA) have been tested. Aperture radii of 15.5 and 21.5 mm are possible for optimum magnet configuration in terms of space utilization. To prevent higher order multipole components, the cuboids must have the largest possible width. With a filling of less than 80%, these stand out clearly (Fig. 6). This limits the usable aperture of the PMQ.

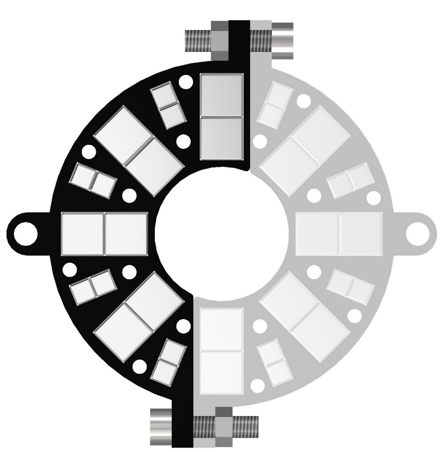


Figure 5: PMQ singlet holder.

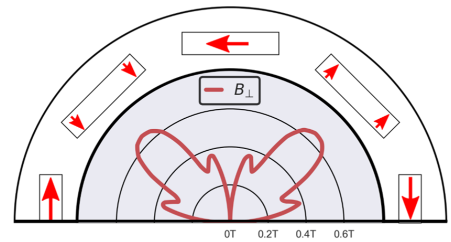


Figure 6: Orthogonal field component on a closed curve along the aperture for a PMQ with a magnet width occupying 70% of the available space.

PMQ Triplet

When combining to form a PMQ triplet, the effective length of the individual PMQ's must be taken into account (Fig. 7). The larger the effective length, the stronger the influence of neighboring singlets. Due to the interaction of neighboring singlets, non-linear effects of the field distribution are amplified and the gradient increases strongly towards the edge of the aperture, which leads to a significant emittance growth when the lens is fully illuminated. This can be compensated either by reducing the illumination or by increasing the singlet spacing. For an 80mm long triplet (without singlet spacing) consisting of two 20mm long outer singlets and a 40mm long inner singlet, the singlet spacing must be increased to 40mm for an aperture radius of 25mm. If the aperture radius is halved, the technically smallest possible distance can be set without negative consequences with regard to beam dynamics.

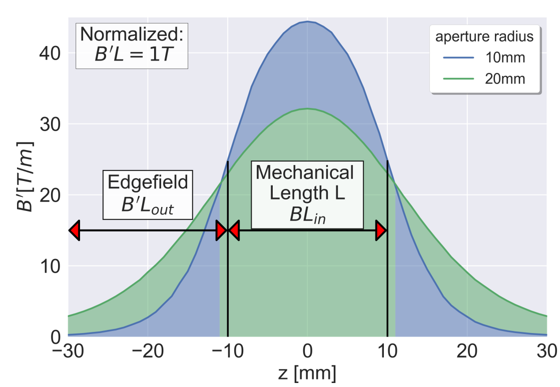


Figure 7: Gradient along the beam axis for singlets with radii of 10 and 20 mm. The larger the aperture radius, the greater the effective length.

BEAM DIAGNOSIS WITHIN A PMQ-TRIPLET

Based on the magnetic envelope for external PMQ, a setup inside a vacuum was developed, with which an optical diagnosis of the beam envelope inside a PMQ triplet can be

ISBN: 978-3-95450-215-8 ISSN: 2226-0366 doi:10.18429/JACoW-LINAC2022-TUPORI30

performed. For image acquisition Rasperry Pi cameras are used, which are controlled by Rasperry Pi Zeros. In a comparable setup at the IAP, comparable cameras and Rasperry Pi's were successfully tested inside a vacuum and inside strong magnetic fields, so that this technique can be directly adopted for this setup [2]. Due to the lack of semiconductors, cameras could only be positioned at three positions in the first prototype. Between the singlets and at the end of the triplet, the beam was observed in two 90° offset planes of the triplet. The magnetic sleeve consists of a single component. The cameras are screwed directly onto the magnetic sleeve using a separate bracket (Fig. 8).

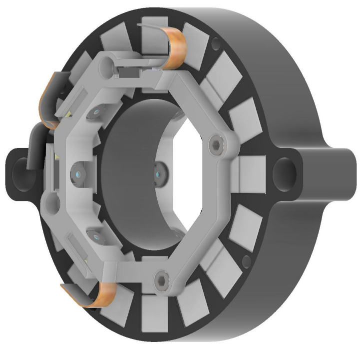


Figure 8: PMQ with screwed-on camera mount.

To align the PMQ, two plates made of PVC are pressed onto the weld seam between the flange and the beam tube. These have two drill holes for threaded rods on which the PMQ can be suspended. For a fixation, additional C-slot rails are inserted in which screws are located, which are pressed against the magnetic sleeve.

For the sharpest possible beam profile, an uncooled aperture was placed in front of the setup. A side effect is a reduction of the background glow from the ion source plasma, which was only 30cm away. The full setup is then integrated in a tube section (see Figs. 9 and 10). First tests were performed with a 5 keV, 150 µA He beam.

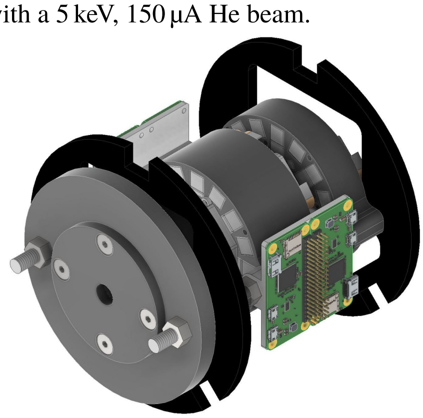


Figure 9: Complete setup of the triplet which is integrated into a CF160 tube section.

Although both beam planes can be distinguished in principle, both envelopes become narrower towards the edge of the image (Fig. 11). For further development of the design, the

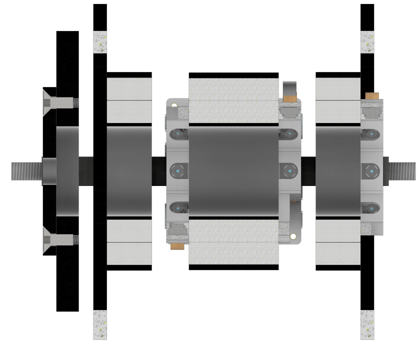
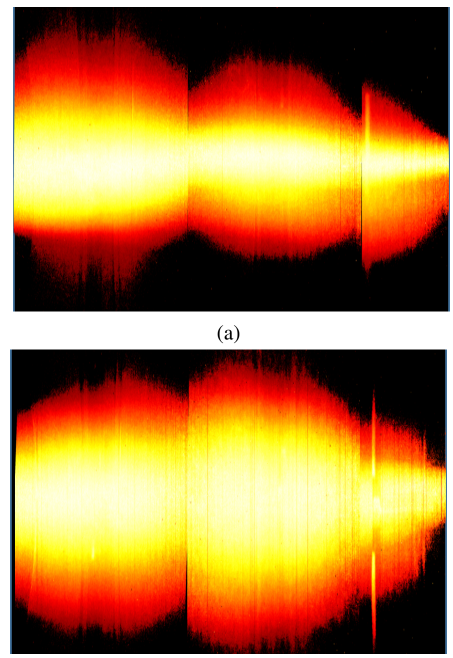


Figure 10: Cross section of the integrated triplet.



(a)

(b)

Figure 11: Beam images of the DFD-Plane (a) and FDF-Plane (b).

number of cameras along the triplet needs to be increased. Due to the 3D printing of the magnetic holders, there is the possibility to integrate them directly into the holder and to position them directly in the center of a singlet. In perspective, the setup will be used for observing high current proton or helium beams. Since the beam is only a few millimeters away from the cameras, the influence of the beam on them should be investigated.

REFERENCES

[1] I. Sexton *et al.*, "The Drift Tube Welding Assembly for the Linac4 Drift Tube Linac at CERN", Cern, Geneva, Switzerland, Rep. CERN-ACC-2014-367, 2014. https://cds.cern.ch/record/2062617

[2] A. Ateş *et al.*, "Non-invasive diagnostics of ion beams in strong toroidal magnetic fields with standard CMOS cameras", *Nucl. Instr. Phys. Res. A*, vol. 877, pp. 69–73, 2018. doi:10.1016/j.nima.2017.09.020