

## Development and testing of a permanent magnet spiral inflector

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A proof-of-concept permanent magnet spiral inflector was constructed and used to successfully inject and accelerate protons in the Solid Pole Cyclotron 2 at iThemba LABS. This article describes the design, construction, and testing of the inflector and discusses its application to other cyclotrons.

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### I. INTRODUCTION

Particles in traditional spiral inflectors are subject to a force from the main magnetic field of the cyclotron and a force from the electrostatic field of the inflector. Conveniently, the electrostatic force is perpendicular to the direction of motion of the central particle. It is, therefore, possible to produce a similar force on the central particle using a magnetic field, where the inflector field  $\mathbf{B}$  is given in terms of the original electric field  $\mathbf{E}$  by,

$$\mathbf{B} = \frac{1}{v} \mathbf{E} \times \hat{v} = -\frac{E_0}{v} \hat{h}_r. \quad (1)$$

Here, the symbols have their standard meanings in spiral inflector literature:  $E_0(s)$  is the strength of the electric field on the central path,  $v$  is the speed of the central particle, and  $\hat{h}_r(s)$  is the unit vector perpendicular to both the central path and the electric field, while  $s$  is the path length [1].

Such a magnetic inflector will follow the same central path as the corresponding electrostatic inflector, but the force experienced by off-axis particles will, in general, not be the same, resulting in different optics for the two devices.

Replacing the electrostatic field with an equivalent magnetic field in this way has potential advantages for high-intensity cyclotrons: (i) The possibility of sparking between the inflector electrodes is removed. This increases the reliability of the cyclotron and reduces potential damage resulting from a badly injected high-power beam. (ii) Electrostatic inflectors prevent space charge neutralization by removing neutralizing particles from the beam

volume through  $\mathbf{E} \times \mathbf{B}$  drift. In a purely magnetic field, the neutralization is more effective, so a magnetic inflector should suffer less from space charge effects in high-intensity beams [2]. (iii) The force produced by a magnet scales with the speed of the particle, so magnetic devices can generally be used at higher energies than electrostatic devices. This opens the possibility of increasing the injection energy, thereby reducing the emittance of the beam and the influence of space charge effects.

There are also a number of constraints that need to be addressed by the design and use of a cyclotron with a magnetic inflector: (i) Unlike an electrostatic inflector where the voltage between the electrodes can be adjusted, a permanent magnet inflector has no adjustment of its field strength. This means it can only be used with beams of a fixed injection rigidity. (ii) The lack of an adjustable inflector field strength reduces the ability to fine-tune the inflector during the operation. (iii) Permanent magnets are limited by the external magnetic fields and radiation levels they can withstand before losing their magnetization.

The idea of a permanent magnet inflector was suggested in [4], where it was foreseen that a series of six-sided Halbach rings could be used to produce the required field. Halbach rings have the advantage of producing nearly uniform internal magnetic fields, while their external fields fall off quickly [5].

Further simulations of permanent magnet designs were performed in [6], where the optics of such devices were analyzed, and it was demonstrated that by modifying the Halbach rings to produce magnetic field gradients, the optics could be adjusted to improve injection into the cyclotron. When ignoring space charge, the magnetic optics were shown to be comparable to electrostatic optics. When including space charge, it is expected that a magnetic inflector will have much better optics than an electrostatic inflector.

In this work, a proof-of-concept permanent magnet inflector, shown in Fig. 1, was constructed and tested. The aim was to show that such a design can be built and

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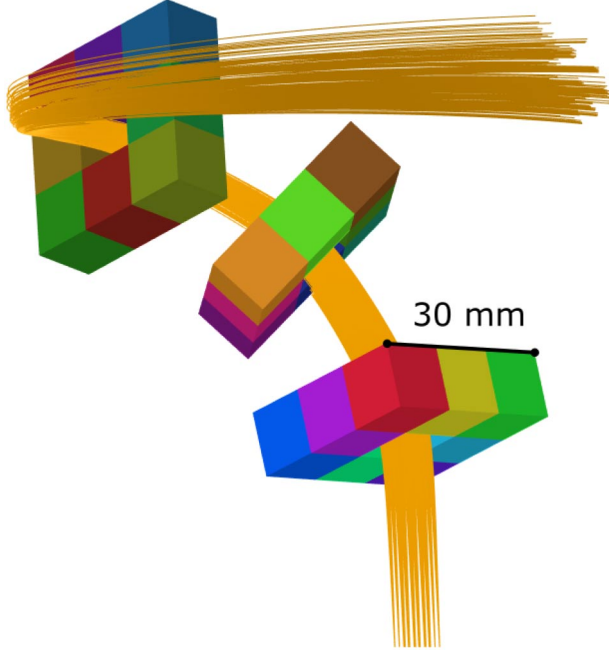


FIG. 1. Simulation of the beam passing through the permanent magnet inflector, performed with OPERA [3].

that it works. As such, the design was kept simple and low-budget with an emphasis on ease of construction, leaving substantial room for improvements and performance optimization in the future.

## II. MAGNETIC SPIRAL INFLECTORS

The coordinate system used with spiral inflectors (see [1] for details) is shown in Fig. 2. It consists of an intermediate right-handed  $[\hat{u}, \hat{h}, \hat{s}]$  frame that is used to construct a final rotated  $[\hat{u}_r, \hat{h}_r, \hat{s}]$  frame, along whose main axes the applied electric field (or, in this case, the magnetic field of the inflector) acts.

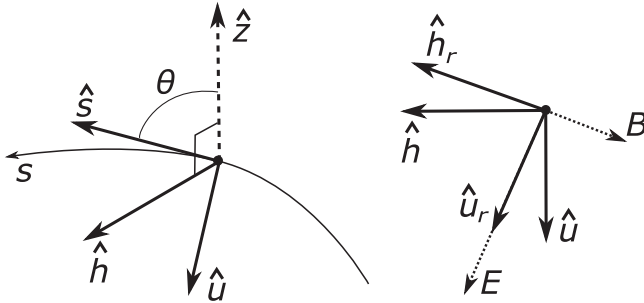


FIG. 2. Left: at a path length position  $s$ , the direction of motion is indicated by  $\hat{s}$ , while the vertical is  $\hat{z}$ . The vector  $\hat{h} \parallel \hat{z} \times \hat{s}$  is always horizontal, while  $\hat{u}$  is chosen so that  $[\hat{u}, \hat{h}, \hat{s}]$  is a right-handed orthogonal frame. Right: in the transverse  $(u, h)$  plane, the axes are rotated to form  $[\hat{u}_r, \hat{h}_r]$  so that the reference electric field points along  $\hat{u}_r$ . For a magnetic inflector, the equivalent magnetic field points along  $-\hat{h}_r$ .

The central path through a spiral inflector is fully described by the inflector height  $A$ , the magnetic radius of curvature  $R_m$ , the tilting parameter  $k'$ , and finally an arbitrary rotation about the axial direction. In electrostatic inflectors, there are two conditions relating the particle speed to the field strengths:

$$B_0 R_m = \frac{mv}{q}, \quad (2)$$

$$E_u A = \frac{mv^2}{q}, \quad (3)$$

where  $B_0$  is the main magnetic field, and  $E_u$  is the constant electric field in the  $\hat{u}$  direction. The horizontal  $E_h(s)$  component acts to produce a force proportional to that of the main magnetic field, thereby altering the effective main field:

$$E_h = E_u k' \sin \theta, \quad (4)$$

where  $\theta(s)$  is the angle between the direction of motion  $\hat{s}$  and the vertical  $\hat{z}$ , as shown in Fig. 2. The equivalent conditions for a magnetic spiral inflector become:

$$-B_h A = \frac{mv}{q}, \quad (5)$$

$$B_u = -B_h k' \sin \theta, \quad (6)$$

where  $B_h$  is the constant inflector magnetic field in the  $\hat{h}$  direction, and  $B_u(s)$  is the field in the  $\hat{u}$  direction. Note that the equations for the magnetic spiral inflector are the same as for two bending magnets: a vertical one with field  $-B_h$  and radius  $A$  and a horizontal one with field  $B_0$  and radius  $R_m$ .

## III. DISCRETE RING INFLECTOR

A permanent magnet can be viewed as a volume with a constant nonzero magnetization. The contribution to the magnetic field at  $\mathbf{x}$  from a small volume element  $dV$  located at  $\mathbf{x}_0$  and containing material with magnetization  $\mathbf{M}$  is:

$$d\mathbf{B} = \frac{\mu_0}{4\pi|\mathbf{r}|^3} (3(\mathbf{M} \cdot \hat{\mathbf{r}})\hat{\mathbf{r}} - \mathbf{M})dV, \quad (7)$$

where  $\mathbf{r} = \mathbf{x} - \mathbf{x}_0$ . A suitable permanent magnet inflector design, therefore, involves selecting a magnetization distribution  $\mathbf{M}(\mathbf{x}_0)$  such that it produces a field on the central path given by Eq. (1). Arranging permanent magnets into this distribution could require the use of many different magnets of varying shapes, sizes, magnetization directions, and strengths.

A simpler approach is to approximate the ideal magnetic field using a number of nonoverlapping Halbach rings,

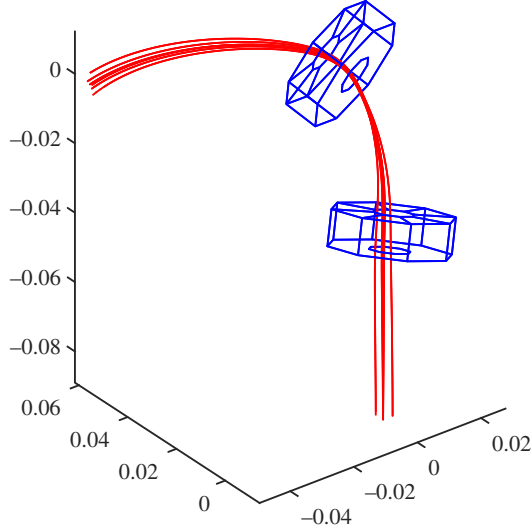


FIG. 3. Design of a spiral inflector with only two Halbach rings. Units are in meters.

where every ring is made of identical and readily available magnets. Numerical tests of this approach revealed the surprising fact that only a very small number of rings are required to inflect the beam along a spiral path and onto the midplane.

Figure 3 demonstrates how an inflector can be made using only two rings. Each ring changes the direction of travel of the beam by about  $45^\circ$ , with the first ring converting the purely vertical motion into combined vertical plus horizontal motion, placing the beam on a helical spiral around the axial direction. The second ring converts the remaining vertical velocity to horizontal motion and injects the beam onto the right orbit.

Although attractive for its simplicity, the two-ring design suffers from a low integral magnetic field along the beam path, limiting its use to beams with low rigidity. For this reason, a three-ring design was used.

The location of each ring  $n$  is indicated by the path length  $s_n$  where it is centered, and the spacing is evenly distributed with  $s_1 = S/6$ ,  $s_2 = 3S/6$ , and  $s_3 = 5S/6$ , where  $S$  is the full length of the inflector.

The Halbach rings were oriented with their main fields aligned along  $-\hat{h}_r(s_n)$ , as shown in Fig. 4. This produces small but nonzero fields in the  $\hat{u}_r$  and  $\hat{s}$  directions at  $s \neq s_n$ .

#### IV. EFFECTIVE FIELD STRENGTH

The discrete ring inflector approximates the field in a spiral inflector, and its central path does not exactly match a true spiral inflector path. To investigate this behavior, it is useful to consider  $\theta$ , the angle between the vertical and the direction of motion. The rate of change is given by

$$\frac{d\theta}{dt} = -\frac{qB_h}{m}. \quad (8)$$

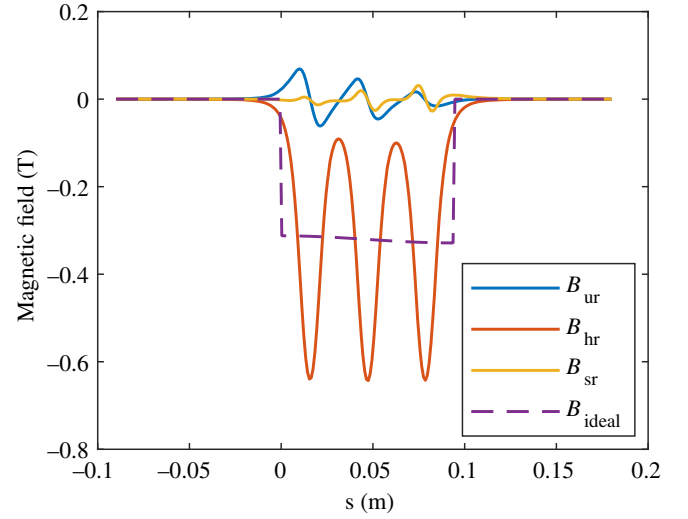


FIG. 4. Magnetic field of the inflector as measured on the central trajectory, showing the  $B_{ur}$ ,  $B_{hr}$ , and  $B_s$  components, as well as the  $B_{hr}$  component of an idealized magnetic spiral inflector described by Eq. (1).

Note that for a true spiral inflector,  $B_h$  is a constant, but for a discrete ring inflector, it can vary significantly. The inflector will bend the beam onto the horizontal plane when  $\Delta\theta = \pi/2$ :

$$\frac{\pi}{2} = -\frac{q}{mv} \int B_h ds, \quad (9)$$

where the integration should extend over the full path length where  $B_h$  is nonzero, so it includes the fringe fields outside the inflector. We can recast the line integral as an approximate length-wise average according to

$$\langle B_h \rangle = \frac{\int B_h ds}{S}. \quad (10)$$

For a spiral inflector, the path length is  $S = \frac{\pi}{2}A$ , so:

$$-\langle B_h \rangle A = \frac{mv}{q}, \quad (11)$$

which provides an effective field version of Eq. (5). Also note that once the inflector has been built,  $A$  and  $\langle B_h \rangle$  are fixed so that it can only accept beams of a set rigidity.

#### V. CUBIC HALBACH RING

Initial proposals for the design of the Halbach rings involved hexagonal or octagonal shapes [4], [6]. This required the individual magnets to be sector-shaped and have a range of magnetization directions. Instead of this, we constructed a Halbach ring made exclusively of identical cubic magnets, shown in Fig. 5.

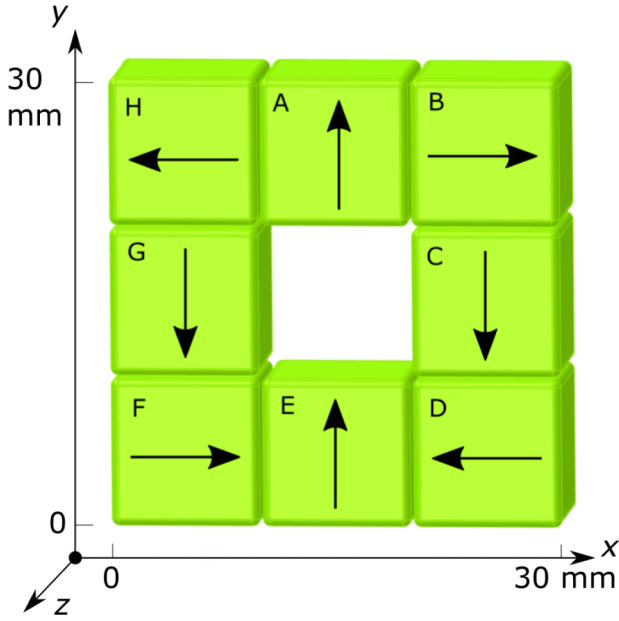


FIG. 5. Magnet arrangement of the Halbach ring showing the direction of magnetization of the cubic magnets. The resulting magnetic field in the pole gap is mostly in the  $+y$  direction.

An idea of the field strength of a cubic Halbach ring can be obtained from the following numerically derived relation:

$$B_{\text{mid}} = 0.58\mu_0 M_0, \quad (12)$$

where  $B_{\text{mid}}$  (in T) is the field measured at the center of the pole gap, and the  $BH$ -behavior of the strong magnetic material is approximated by treating the magnets as regions with constant equivalent magnetization  $M_0$  (in A/m). Note that  $B_{\text{mid}}$  does not depend on the cube side length.

The magnetic field in the pole gap and around the magnet is shown in Fig. 6. The field is strong inside the pole gap and falls off quickly outside the ring. Figure 7 shows the variation in  $B_x$  and  $B_y$  across the pole gap.

The variations in the magnetic field can be expressed by the best-fit quadratic functions:

$$B_x = 0.0033xy, \quad (13)$$

$$B_y = 1 + 0.0017x^2 + 0.0120y^2, \quad (14)$$

where the main field (in T) and has been normalized to 1 T, while  $x$  and  $y$  are expressed in mm. Note that the 2D divergence ( $\partial B_x/\partial x + \partial B_y/\partial y$ ) is not zero, and therefore the fields cannot be expressed with a 2D-multipole expansion. The reason for this is that the Halbach ring has significant 3D behavior, and the longitudinal derivative  $\partial B_z/\partial z$  is not negligible so that while the potential obeys the 3D Laplace equation, it does not obey the 2D-Laplace equation in the  $(x, y)$  plane.

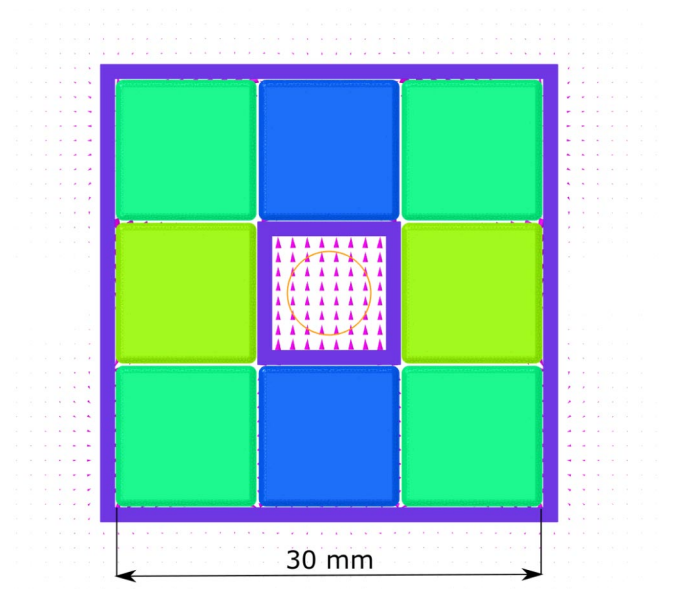


FIG. 6. The magnetic field vectors on the transverse plane, as simulated with OPERA. A circle with a diameter of 75% the gap width is shown. Note the presence of the 1 mm thick aluminum housing surrounding the ring on the outside and inside.

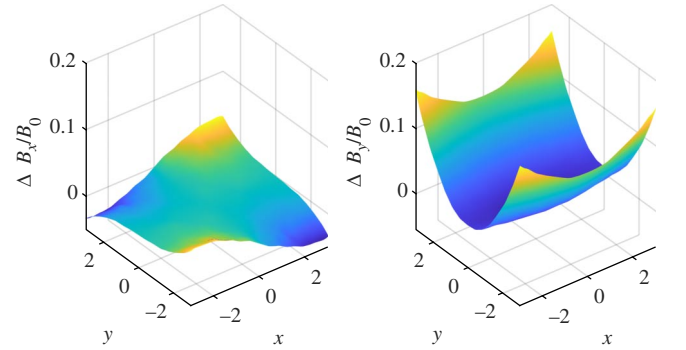


FIG. 7. Variation in the magnetic field on the transverse  $(x, y)$  midplane of the ring ( $z = 0$ ). The  $x$  and  $y$  axes are in mm, and the field variation is normalized with respect to the field in the center of the ring.  $B_x$  (left) shows a predominant  $xy$  behavior, and  $B_y$  (right) shows a predominant  $y^2$  and  $x^2$  behavior. Note that the heights of the two graphs are on the same scale, but the colors are not, in order to better show the surface shape.

These values can be compared to an electrostatic inflector, where the most prominent variation is of first order and due to the curvature of the central path. For inflector C1 at SPC2 (see Sec. VI for more details about the inflector), the field at the transverse plane halfway along the inflector is numerically found to be:

$$E_{u_r} = 1 + 0.0164u_r - 0.0006h_r, \quad (15)$$

$$E_{h_r} = -0.002 - 0.0024h_r, \quad (16)$$

TABLE I. Parameters of the inflector.

|                                     |                                  |
|-------------------------------------|----------------------------------|
| Magnetic bending radius ( $R_m$ )   | 49 mm                            |
| Inflector height ( $A$ )            | 60 mm                            |
| Tilt parameter ( $k'$ )             | 0.38                             |
| Halbach ring beam gap               | $8 \times 8$ mm square           |
| Halbach ring magnet size            | $10 \times 10 \times 10$ mm cube |
| Halbach ring maximum field strength | 0.65 T                           |

where the main field (in V/m) has been normalized to 1 V/m, while  $u_r$  and  $h_r$  are expressed in mm. The quadratic terms are neglected since they have coefficients smaller than 0.001.

On a circle with radius 3 mm, or 75% of the gap width, as shown in Fig. 6, the  $E$  field of the electrostatic inflector has a maximum variation of 6%, while the  $B$  field of the Halbach ring has a maximum variation of 10%. The 3 mm displacement is in line with the original design of the injection beam line of inflector C1, where the maximum half-widths at the inflector entrance were estimated to be 3 mm  $\times$  66 mrad in the transverse directions, with a 0.5% momentum spread [7].

## VI. INFLECTOR DESIGN

The inflector chosen for this study was inflector-C of the SPC2 injector cyclotron at iThemba LABS. This inflector is described in Table I and has been studied in detail; several optimized electrostatic versions of inflector-C have been tested in the past [8].

It is important that the inflector field does not influence the beam motion in the rest of the cyclotron. As shown in Fig. 8, the field on the midplane, in the area where the first orbit lies, is around 0.2 mT, which is 0.05% of the main field.

The deviation between the central path of the true spiral inflector-C and the central path of the discrete inflector designed here is 2 mm at its greatest.

## VII. OPTICS

Since this work was a proof-of-principle construction, the discrete ring inflector was not optimized for focusing, dispersion, or acceptance. The optics were, however, investigated numerically and found to be largely similar to that of electrostatic inflectors. This is reassuring since there are factors that might influence the optics in novel ways: the large longitudinal variations in field strength  $\partial B/\partial s$  due to the discrete separated rings, combined with the curved nature of the central path, will result in transverse field gradients, with effects similar to edge focusing and defocusing in bending magnets. Furthermore, the magnetic field in the Halbach rings has an appreciable second-order variation in the transverse plane, meaning second-order optics may play an important role.

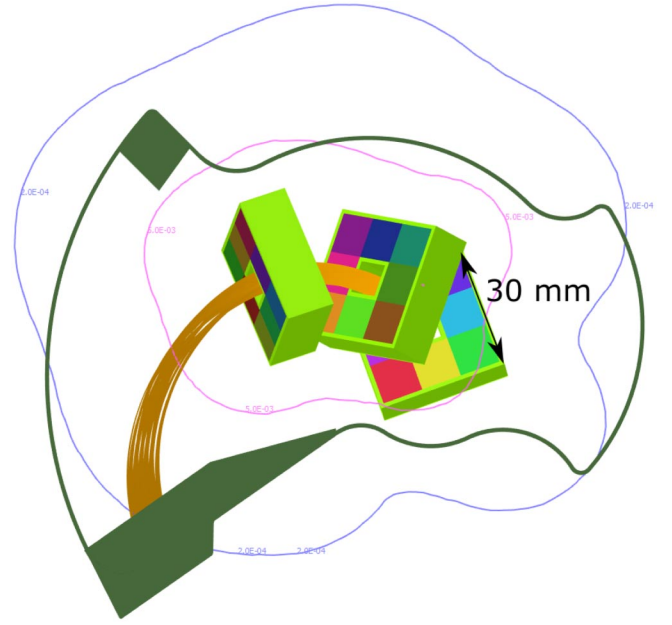


FIG. 8. Contours of the inflector field on the midplane, showing the 5 and 0.2 mT lines, as well as the rf shielding around the inflector.

Figure 9 provides an overview of the optics of the magnetic inflector and compares it to the electrostatic C1-inflector. For this simulation, a uniform ellipsoidal beam with half-widths of 3 mm  $\times$  30 mrad in the

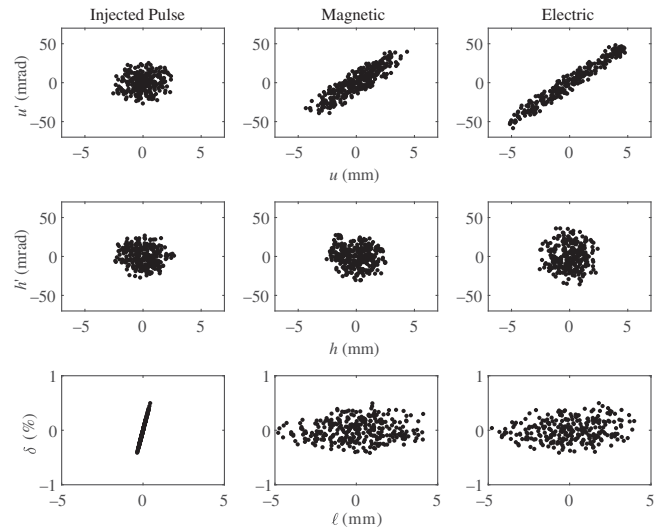


FIG. 9. Phase-space projections of a short beam pulse passing through the inflector. The top row is the projection on the  $(u, u')$  phase space, the middle row is  $(h, h')$ , and the bottom row is  $(\ell, \delta)$ . The left column is the input beam as measured at the collimator just upstream of the inflector. The middle column is the output beam at the first acceleration gap when using the discrete magnetic inflector, and the right column is the output beam when using the electrostatic C1-inflector. The magnetic and electric inflectors have roughly comparable projected optics.

transverse plane and 0.5% momentum spread was used. Since the inflector is a time-independent system, a pulse was used with no  $\ell$ -spread. The beam was focused at the inflector entrance collimator, but the ray tracing actually started 9 cm upstream of the inflector, in a region where the main magnetic field is zero, to account for the effect of the sharp growth of the main magnetic field in the axial bore of the yoke. The simulation endpoint was at the first acceleration gap about 6 cm downstream of the inflector. At the end point, the magnetic and electric deflectors seem to produce phase-space projections that are of similar magnitude.

Numerically measuring the transverse dispersion of the deflectors in the above simulation gave:

$$\begin{bmatrix} (u|\delta) \\ (u'|\delta) \\ (h|\delta) \\ (h'|\delta) \end{bmatrix}_{\text{Magnetic}} = \begin{bmatrix} -1.660 \\ -13.30 \\ -0.8754 \\ -7.668 \end{bmatrix}, \quad (17)$$

and,

$$\begin{bmatrix} (u|\delta) \\ (u'|\delta) \\ (h|\delta) \\ (h'|\delta) \end{bmatrix}_{C1} = \begin{bmatrix} -2.436 \\ -19.83 \\ -0.2079 \\ -16.34 \end{bmatrix}, \quad (18)$$

where  $u, h$  are in mm,  $u', h'$  are in mrad, and  $\delta$  is measured in %. For most of these terms, the magnetic inflector is less dispersive than the electrostatic C1-inflector.

### VIII. DEMAGNETIZATION

A major failure mode for permanent magnets placed in large external magnetic fields is the demagnetization of the magnetic material. The course-grained sintered NdFeB magnets used in this magnetic inflector have an easy axis along which the magnetization generally points, corresponding to the  $c$ -axis of the tetragonal crystals. The directions of the  $c$ -axes of the individual grains are mostly aligned during manufacturing, producing a net magnetization. We indicate the direction of magnetization by  $\hat{m}$ , so the total magnetic field in a magnet can be split into parts parallel and perpendicular to  $\hat{m}$ :

$$\mathbf{H} = H_{\parallel} \hat{m} + \mathbf{H}_{\perp}. \quad (19)$$

The normal hysteresis graph is a plot of  $B$ - $H_{\parallel}$ . An  $H_{\parallel} > 0$  field reinforces the magnetization and will not demagnetize the material. When  $H_{\parallel} < 0$ , the material starts to demagnetize as  $H_{\parallel}$  approaches  $-H_{ci}$ , the intrinsic coercivity. The start of demagnetization is seen as the knee in the second quadrant of the M-H curve.

The presence of a transverse field complicates the situation. Experimental measurements of a single crystal

show that a perpendicular field of  $B_{\perp} = 7$  T is required to produce irreversible saturation in the perpendicular direction [9]. The Stoner-Wohlfarth model effectively treats the material as a collection of single crystals undergoing coherent rotation [10]. For smaller fields, it predicts that the magnetization is rotated by an angle  $\sin(\alpha) = H_E/H_A$ , where  $H_E$  is the external perpendicular field and  $H_A$  is the so-called magnetocrystalline anisotropy field of around 5500 kA/m for NdFeB. For an external  $B_{\perp}$  field of 0.5 T, similar to the operational field of the inflector, this results in the magnetization direction rotating by  $4^\circ$ , which is not significant. However, the Stoner-Wohlfarth model is known to overestimate the coercivity of course-grained sintered NdFeB and should only be used as a first-order baseline [11].

Another approach is an empirical model based on many measurements of sintered NdFeB magnets [12]. It shows that a perpendicular field producing 10% demagnetization must be about 1.8 times as large as an antiparallel field producing the same demagnetization. Both of these models show that antiparallel demagnetization is likely to occur first, and we therefore neglected  $H_{\perp}$  in this analysis.

Simulations of the inflector showed that a number of magnets in the third ring were most susceptible to demagnetization due to the orientation of this ring relative to the main magnetic field in the cyclotron. In the first two rings, the main field produces larger  $H_{\perp}$  and smaller  $H_{\parallel}$  components, making these rings less susceptible to demagnetization.

The calculated parallel magnetic field in the third ring is shown in Fig. 10. In the absence of an external main cyclotron field,  $-H_{\parallel}$  reaches 750 kA/m, which is well below the  $H_{ci}$  of N38 magnets of around 900 kA/m. When the operational external field of 0.38 T is applied, the vast majority of the ring remains far away from  $H_{ci}$  with the maximum  $-H_{\parallel}$  of 850 kA/m only reached in the corners of some magnets. The field where demagnetization starts to play an important role is around 0.6 T. At a field of 0.9 T, two of the magnets are almost completely demagnetized, and the maximum  $-H_{\parallel}$  reached is 1220 kA/m. In the Halbach ring coordinate system shown in Fig. 10, the main cyclotron field at the third Halbach ring points mostly in the  $-x$  direction that leads to demagnetization of those magnets with magnetizations pointing in  $+x$ , as is expected.

A number of experiments were performed to investigate the demagnetization of the inflector. This involved installing the inflector in the cyclotron and exposing it to the main magnetic field for 15 min. It was then removed, and the magnetic field at the center of each ring was measured. The results are shown in Table II. For main magnetic fields equal to or less than the operational field of 0.38 T, no demagnetization was detected, in line with the simulations. At a large main field of 0.9 T, the rings show significant demagnetization, also in line with the simulations.

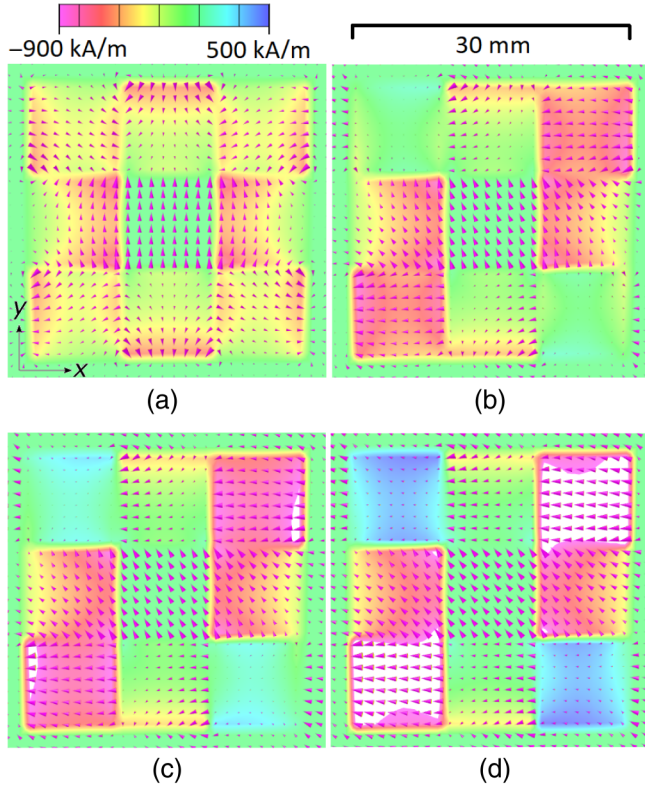


FIG. 10. The  $H_{\parallel}$  field inside the magnets (colors) and the total  $H$  field (arrows) on the midplane of the third Halbach ring in the inflector (a) is without an external field, (b) is with the operational main cyclotron B field of 0.38 T, (c) is with a main field of 0.6 T, and (d) is with a main field of 0.9 T. The white areas correspond  $H_{\parallel} < -900$  kA/m where demagnetization will occur.

The third ring has more demagnetization than the second ring, and the second ring more than the first, in line with the fact that the perpendicular field at the rings follow  $H_{\perp 3} < H_{\perp 2} < H_{\perp 1}$ . This shows the perpendicular fields do not play an important role in demagnetization, supporting our assumption of ignoring  $H_{\perp}$  in the analysis.

The low-grade N38 magnets used here have  $H_{ci}$  values of around 900 kA/m, and this is the limiting factor in demagnetization. It is therefore suggested that higher-grade magnets be used in future work. The AH series, for example, has  $H_{ci}$  around 2700 kA/m. In the simulation

TABLE II. Field strengths of the Halbach rings after exposing the inflector to different main cyclotron fields.

| Main field (T) | Ring 1 (T) | Ring 2 (T) | Ring 3 (T) |
|----------------|------------|------------|------------|
| 0.00           | 0.64       | 0.64       | 0.64       |
| 0.15           | 0.64       | 0.64       | 0.64       |
| 0.30           | 0.64       | 0.64       | 0.64       |
| 0.38           | 0.64       | 0.64       | 0.64       |
| 0.9            | 0.59       | 0.51       | 0.37       |

of  $H_{\parallel}$ , an inflector with such magnets is able to withstand main fields in excess of 2.5 T.

## IX. CONSTRUCTION

The magnets used were neodymium type N38 with a protective nickel coating, sourced from a local store for a total cost of ZAR 750. They had an effective saturation magnetization of 920 kA/m, obtained by comparing the measured field of the Halbach rings with the calculated field, as shown in Fig. 11.

The magnets experience substantial forces when assembled into a Halbach ring. To keep the magnets in place, they were mounted in aluminum containers, shown in Fig. 12, which also served to protect the magnets from the beam. During the assembly phase, super glue was initially used to hold the magnets in place, but later on it was found that the assembly could be done without glue if the magnets were installed in the order A, E, H, B, D, F, C, and G where the naming is shown in Fig. 5. The assembly process was helped by placing the bottom of the container on a steel table so that the assembled magnets were attracted to the table.

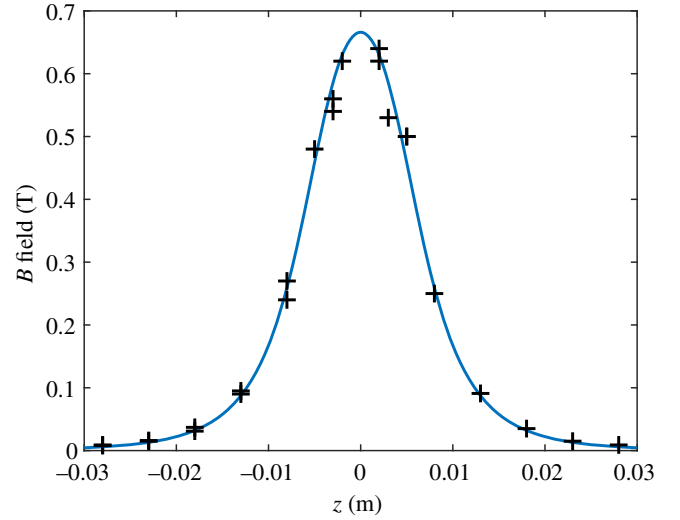


FIG. 11. Field strength  $B_y$  of the Halbach ring measured at various axial positions: calculated values (solid line) and measured values (crosses).

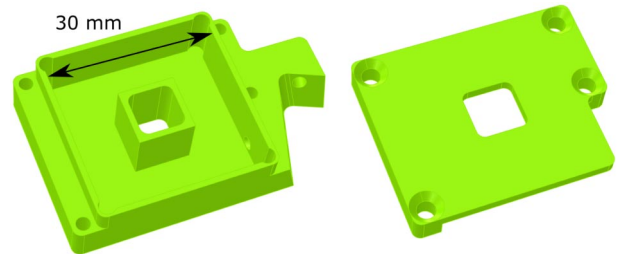


FIG. 12. Design of the mounting container (left) and lid (right).

The three Halbach rings and the upstream collimator were bolted to a PVC mounting fork so that they were electrically isolated, and the beam current falling on each part was measured separately for diagnostic purposes.

The mounting fork had to be strong enough to withstand the magnetic forces on the Halbach rings. Fortunately, the total magnetization of the magnets in each Halbach ring is zero, meaning a uniform main magnetic field would not exert a net moment on the ring, and a main magnetic field with a constant gradient would not exert a net linear force on the ring. These symmetry properties limit the forces experienced by the Halbach rings.

The fork, collimator, and mounting containers were all manufactured in-house at iThemba LABS with CNC machining and are shown in their final assembled configuration in Fig. 13, while a photo of the inflector is shown in Fig. 14.

The outgassing of the plastic, superglue, and magnets did not pose a noticeable problem. During the testing of the magnetic inflector, the pressure in the main chamber of the

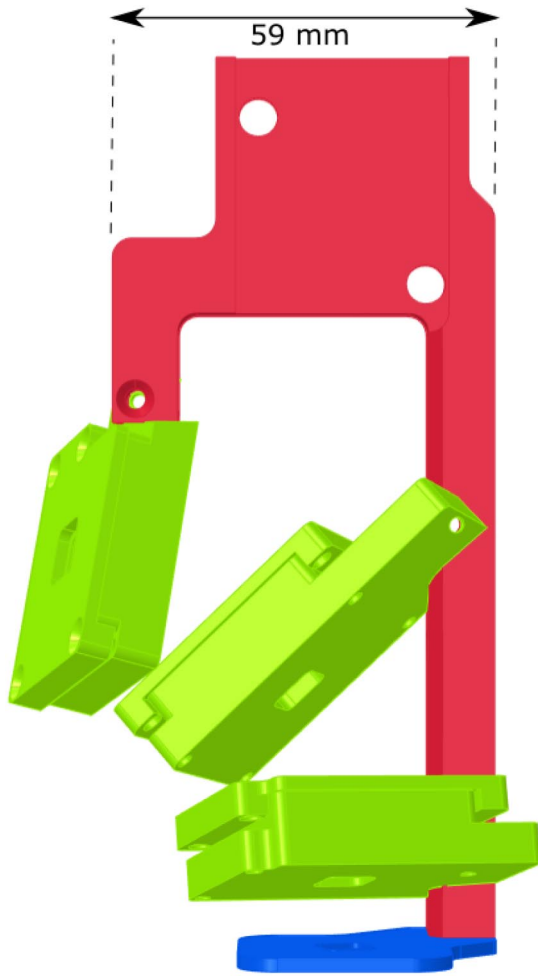


FIG. 13. CAD model of the constructed inflector showing its mounting fork (red), collimator (blue), and Halbach ring containers (green).



FIG. 14. Photo of the magnetic inflector.

cyclotron was  $4.6 \times 10^{-6}$  mbar, which is somewhat higher than the normal value of up to  $2.0 \times 10^{-6}$  mbar with the beam on (SPC2 can achieve much better vacuum levels when running with its cryopumps, but they are currently turned off).

## X. TESTING SETUP

The permanent magnet inflector was tested in the Solid Pole Cyclotron 2 (SPC2) at iThemba LABS, which is usually used as the preaccelerator for the Separated Sector Cyclotron (SSC) [13]. The inflector required a main magnetic field of 0.38 T to operate. This corresponds to the cyclotron settings shown in Table III.

TABLE III. Cyclotron settings of the SPC2 cyclotron when using the magnetic inflector.

| Accelerated particles     | Protons  |
|---------------------------|----------|
| Main magnetic field       | 0.38 T   |
| Harmonic number           | $h = 2$  |
| Injection energy          | 16.8 keV |
| Extraction energy in SPC2 | 1.60 MeV |
| Extraction energy in SSC  | 32.0 MeV |

The injection optics of SPC2 are described in detail in [7]. For focusing the beam at the entrance to the cyclotron yoke, two triplets are used, which are set up as a telescopic system and mounted on a frame that can rotate about the beam direction to produce  $x$ - $y$  correlations in the beam. This is followed by two solenoids for focusing the beam at the inflector collimator. A buncher is located upstream of the solenoids.

SPC2 has exchangeable inflectors used for injecting the beam on different orbit geometries, and a new inflector can be installed in around 2 h without venting the cyclotron. During the operation, the  $x, y, z$  position of the inflector can be adjusted, as well as its rotation about the axial direction.

## XI. RESULTS OF TESTING

In December 2025, a proton beam was successfully injected into SPC2 using the magnetic inflector and accelerated, as shown by the beam intensity plot in Fig. 15. The beam current measurements on the collimator and Halbach rings were helpful in beam tuning and in positioning the inflector.

Injection efficiency for SPC2 is measured between the last Faraday cup upstream of SPC2 and the radial probe located after half a turn (and two acceleration gaps) in the cyclotron. For an initial beam of 50  $\mu$ A protons, the magnetic inflector obtained an injection efficiency of 27%, which is very typical for a traditional SPC2 spiral inflector. The beam pattern through the rest of the cyclotron seemed very clean, compared to the usual electrostatic case.

It is notable that the magnetic inflector achieved similar levels of transmission to the electrostatic inflectors, despite having a fixed magnetic field strength that does not allow

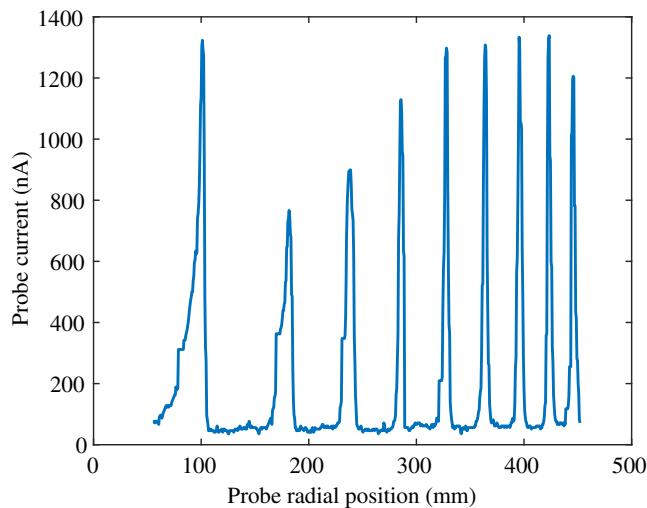


FIG. 15. Orbit profile inside SPC2 when using the magnetic inflector. The measurements were taken with a differential radial probe and show all nine crossings of the probe before extraction. The raw data is available at [14].

fine-tuning. This can be partly attributed to the large amount of freedom that SPC2 provides for fine-tuning the position of the inflector during operation: full  $(x, y, z)$  translation and a rotation about  $z$ .

Note that SPC2 operates at low beam currents where space charge effects can be ignored, and any improvement due to charge neutralization was not expected to be observed.

## XII. RADIATION DAMAGE

The inflector will be subjected to several sources of radiation. Protons from the main beam that directly impact the inflector will have relatively low energies and will be stopped by the mounting containers (the range of 1 MeV protons in aluminum is around 10  $\mu$ m). The energy from these collisions will be mostly dissipated as heat, and care must be taken not to warm up the magnets, since they are more easily demagnetized at higher temperatures. This might require active cooling of the inflector for very high beam currents. A small fraction of the proton energy will be released as bremsstrahlung x-rays that could penetrate the magnets, but NdFeB is relatively resistant to damage from x-rays [15].

Alternatively, protons lost at high energies will produce a large mixture of radiating particles upon striking the cyclotron body, including gammas and neutrons. The magnets are relatively resistant to gammas [15], but high-energy neutrons are particularly damaging [16]. Fortunately, most of the high-energy neutrons will be emitted in the forward azimuthal direction in the collision and not toward the center of the cyclotron. The effect of low-energy neutrons is uncertain, with some studies reporting no damage [15], while others measure a significant effect [17], particularly from damage related to the  $^{10}\text{B}(n, \alpha)^7\text{Li}$  neutron capture reaction. Future research is required to determine the expected lifetime of an NdFeB inflector.

Interestingly, it is reported that SmCo magnets are substantially more radiation resistant than NdFeB. A collection of experiments using reactor-produced neutrons shows that NdFeB starts to lose magnetization after receiving  $10^{14}$ – $10^{15}$  n/cm<sup>2</sup>, while SmCo showed the same behavior at  $10^{19}$ – $10^{20}$  n/cm<sup>2</sup> [18]. NdFeB has a higher magnetic field ( $B_r = 1.3$  T for N38) than SmCo ( $B_r = 1.1$  T for high coercivity grade SC-2826), but this is only a 15% reduction, and it should be possible to construct a magnetic inflector out of SmCo magnets instead.

## XIII. FUTURE APPLICATIONS

In this study, a low main field of 0.38 T was used. Practical high-intensity accelerators use higher fields, so let us consider a  $B_0 = 1.5$  T proton cyclotron. For simplicity, also set  $k' = 0$ , so that the inflector only has a constant  $B_h$  field.

TABLE IV. Selected values of the inflector height and the corresponding magnetic bending radius and injection voltage (protons,  $B_0 = 1.5$  T,  $k' = 0$ ,  $R_m/A = 0.33$ ).

| Height $A$<br>(mm) | Magnetic radius<br>$R_m$ (mm) | Injection voltage<br>$V_{in}$ (kV) |
|--------------------|-------------------------------|------------------------------------|
| 25                 | 8.3                           | 7.3                                |
| 50                 | 17                            | 29                                 |
| 100                | 33                            | 117                                |
| 200                | 66                            | 470                                |

The inflector design now comes down to selecting appropriate values of  $A$ ,  $R_m$ ,  $\langle B_h \rangle$  and  $mv/q$  so that the two rigidity relations, Eqs. (2) and (11), are satisfied. Combining these equations gives

$$\frac{R_m}{A} = \frac{-\langle B_h \rangle}{B_0}. \quad (20)$$

This means any ratio of  $\langle B_h \rangle/B_0$  can be accommodated by selecting a design with a corresponding aspect ratio  $R_m/A$ . In essence, lower inflector fields can be compensated for by having longer inflector path lengths over which to act.

The three-ring inflector presented here has a  $\langle B_h \rangle$  of 0.31 T. But it is clearly not optimized and has a lot of unused space that could potentially be filled with additional magnets. Using sector magnets instead of cubes also enhances the field. As a rough estimate, suppose that this increases the average field to  $\langle B_h \rangle = 0.5$  T. The possibility of using stronger grade magnets also exists, but most of the high- $H_{ci}$  grades have similar magnetizations to the N38 already in use.

This leads to an aspect ratio of  $R_m/A = 0.33$ . Selecting an inflector height  $A$  now completes the design, resulting in corresponding values of  $R_m$  and the rigidity (or equivalently the injection energy), displayed in Table IV.

We note that the injection energy for a magnetic inflector can be much greater than for electrostatic deflectors. The designs given above are feasible, provided they can fit into the cyclotron and inject particles onto the correct orbit.

For comparison, the three-ring magnetic inflector tested in this study had a large  $R_m/A$  ratio of 0.82 in addition to its low average field  $\langle B_h \rangle = 0.31$  T. This resulted in the low main magnetic field of 0.38 T and corresponded to the low injection energy of 16.8 keV (suitable for SPC2).

Finally, we note that using  $k' \neq 0$  somewhat reduces the available  $\langle B_h \rangle$ , since the permanent magnet field needs to produce a  $B_u$  as well.

#### XIV. CONCLUSION

A proof-of-principle magnetic spiral inflector has been designed, constructed, and successfully tested.

Practical considerations limited the average magnetic field  $\langle B_h \rangle$  in this inflector, and the preexisting design of inflector-C fixed the aspect ratio  $R_m/A$ , resulting in a low main magnet field and low injection energy.

But by increasing  $\langle B_h \rangle$  and  $R_m/A$ , it should be possible to construct magnetic deflectors that can handle higher main fields and very high injection energies.

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#### DATA AVAILABILITY

The data used to generate Fig. 15 are available from Ref. [14].

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