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# Development of a permanent magnet alternative for a solenoidal ion source

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ABSTRACT

The most sensitive desktop-sized ionizer utilising electron bombardment is currently the solenoidal ion source. We present an alternate design for such an ion source whereby the solenoidal windings of the electromagnet are replaced by a shaped cylindrical permanent magnet in order to reduce the complexity and running costs of the instrument. Through finite element modelling of the magnetic field in COMSOL and experimental measurements on a small-scale prototype magnet stack, we demonstrate the required shape of the permanent magnet in order to generate the needed field, and the necessity of soft iron collars to smooth fluctuations along the central axis.



## 1. Introduction

Crucial to a wide range of areas within research and industry, mass spectrometry has been continually refined to provide higher sensitivities and better mass discrimination. Whilst the current generation of mass spectrometers can meet the requirements of the majority of applications, new advances in the field of atomic and molecular beams are necessitating better technology [1]. In particular, analysing small quantities of neutral species (such as in a scanning helium microscope or SHeM [2–4]) remains a significant challenge. The limiting factor for instrument sensitivity is typically the ionizer, responsible for ionising the atoms or molecules of interest prior to mass filtering [5]. The most common method to produce an ion is electron bombardment, and correspondingly the majority of work has focused on further improving the performance of this particular type of ionizer. To date, the most sensitive electron impact ionizers applicable for a desktop instrument have been solenoidal ion sources in which a magnetic field is used to confine a dense electron population coaxial to the atomic beam. The electrons can be made to execute reflexive trajectories along the magnetic field lines, leading to the creation of a large, stable ionisation volume and hence increasing the probability of ionisation. Sensitivities of 0.8 A/mbar for neutral helium have been recently reported [6,7].

The work presented seeks to improve the implementation of such an ion source by removing the solenoid responsible for the magnetic field, and replacing it with a shaped permanent magnet. For compact assemblies requiring a large magnetic field, permanent magnets are more appropriate as they remove the progressively more acute problems of power supply, cooling and winding accuracy. Previous ion sources of this design have not only had a large percentage of the physical size of the final instrument made up by the cooling system (to dissipate greater than 1.5 kW of heat from the windings), but have been difficult and expensive to construct due to the accuracy needed in winding the electromagnet [7,8], thus motivating the change.

We present a method for designing hollow cylindrical permanent magnet assemblies with tailored axial flux densities that can be used to replace complex electromagnetic solenoids in future ion sources. The resultant magnetic field along the axis of the device has been modelled in COMSOL, a commercially available three-dimensional FEA software package, and then compared to experimental results for a small-scale prototype magnet in the same design.

## 2. Methodology

### 2.1. Principles of operation

The operation of a solenoidal ion source has been discussed in detail previously [6,7], with the major elements of the design shown schematically in Fig. 1. The solenoidal winding produces the required magnetic field and defines the axis of the device. The liner (surrounded by the windings) is supplied with a positive

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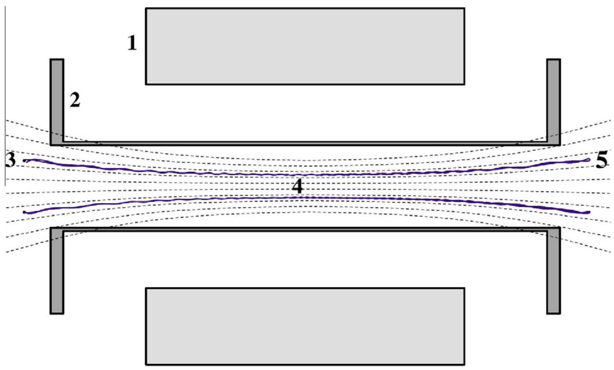


**Fig. 1.** Schematic showing the major elements for a solenoidal ion source. (1) Solenoidal windings of an electromagnet. (2) Electrically biased solenoid liner. (3) Electron trajectories emerging from the circular cathode, guided along the magnetic field lines, condensing at the highest flux density at (4), until they are reflected by the drop in electrical potential at (5). Image courtesy Alderwick et al. [7].

bias voltage to confine the ions and electrons radially to the device axis. Electrons responsible for ionising the species of interest originate at the cathode, a simple circular filament coaxial with the rest of the device, and are accelerated into the centre of the device through careful choice of potentials. Executing helical trajectories along the magnetic field lines, the confined electron population forms a cylinder along the axis of the source, with reflexive trajectories back and forth along the full length (in the absence of loss mechanisms). The population quickly builds to a stable equilibrium due to the space charge in the vicinity of the filament, and the ion source moves into a stable and sensitive mode of operation.

The interplay of the electric and magnetic fields employed is critical to source performance, as these affect the density and shape of the confined electron population responsible for ionisation. Alderwick et al. [7] found that the simplest case, a constant field strength solenoidal magnetic field, results in the loss of ion extraction directionality, and an excessive ion residence time due to the creation of trapping potential wells (causing a reduction in ionizer performance). A more optimal solution (as indicated through prior modelling of the space charge within the ionizer [6,7]) requires several changes to the source design, among them having the magnetic field engineered to not only confine the electron population but to also aid in controlling the potential. In particular, having the field strength increase over the length of the device causes the electron cloud to become more confined and thus progressively depresses the axial electric potential as the electron space-charge contribution increases. Any ions created now experience a force pulling them towards the exit of the ion source, improving the efficiency of extraction.

Beyond simply replacing the solenoid, the move from an electromagnet to a permanent magnet should provide a simpler means to achieve the monotonically increasing axial magnetic field discussed above. Previous solenoidal ion sources have attempted to replicate this field shape by chaining multiple individually powered solenoids end-to-end with progressively larger currents supplied (up to 30 A) [6]. Such designs further increase the complexity, and hence cost, of building the instrument. While a hollow cylindrical permanent magnet will exhibit a similar large scale field as a simple solenoid, a smoothly increasing field obviously necessitates a different shape, or a combination of magnets.

## *2.2. Magnetic field modelling*

To find an arrangement of permanent magnets that would achieve the desired field to a first approximation, an analytical model was developed. Regions of uniform magnetisation may be represented by a set of surface currents, and so a cylindrical permanent magnet can be represented by a single current sheet around its circumference. A hollow cylindrical magnet will thus have a second current sheet running along the exposed inner surface, with the direction of rotation opposing the rotation of the outer current sheet. The interaction of these counter-rotating current sheets act to reduce the axial flux density along the length of the hollow magnet. Calculating the axial magnetic flux via Biot-Savart's law yields:

$$B_{\text{axis}} = \frac{\mu_o M}{2}((\cos\alpha_1 + \cos\alpha_3) - (\cos\alpha_2 + \cos\alpha_4)),$$

where $B_{\text{axis}}$ is the axial magnetic flux due to the counter-rotating current sheets, $M$ is the magnetisation of the permanent magnet (A/m), $\mu_o$ is the magnetic permeability of free space, and the angles $\alpha_n$ are as defined in Fig. 2 below.

Using this formulation, the axial field for different magnet geometries was able to be quickly modelled, with the ratio of the inner-to-outer diameter found to be of particular importance. The simplest option to achieve the required field shape proved to be a stepped/discrete approximation of a quarter period cosine profile as shown in Fig. 2b. The choice to design shapes from annular magnets of constant inner diameter and varying outer diameter was made to simplify the construction of a prototype from off-the-shelf neodymium iron boride magnets. Additionally, the modelling showed that increasing the number of magnets to better approximate the quarter period cosine profile (or even building a single magnet shaped to this profile) caused no meaningful improvement to the smoothness of the axial magnetic field. Whilst the modelled axial field within the magnet displays the monotonic increase required for efficient ion extraction, the analytical model is overly simplistic. In particular, it does not take into account the exposed faces of the magnets perpendicular to the axis. These surfaces are magnetised normally, and will produce unwanted distortions in the observed axial magnetic field. Consequently, to model the fields to the necessary degree of sophistication, the magnet design

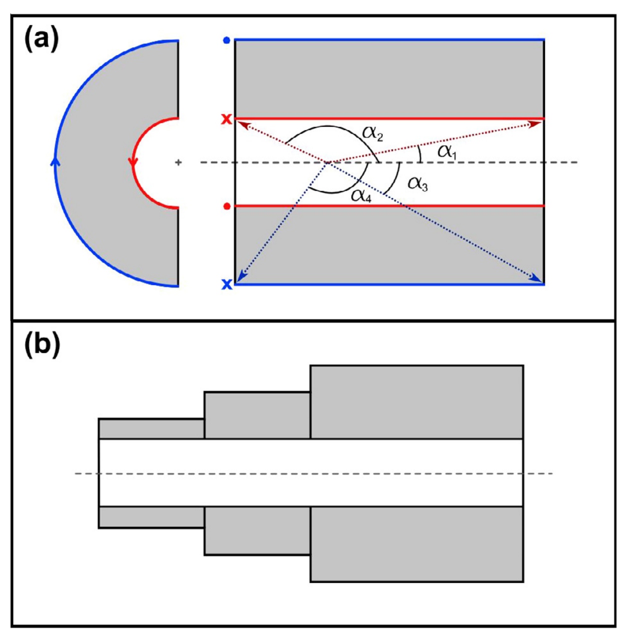


**Fig. 2.** (a) Sectioned schematic diagram of a hollow, cylindrical permanent magnet as a pair of counter-rotating current sheets (red lines indicate the current along the inner surface, and blue the current around the outer surface). (b) Demonstration of how several different sized cylindrical magnets can be used to approximate a quarter period cosine profile. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)