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# The influence of stray DC magnetic fields in MeV ion nanobeam systems

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ABSTRACT

This paper evaluates the lens aberrations in microbeam and nanobeam systems caused by stray DC magnetic fields. Stray DC fields are far less influential on focussed beam spots than stray AC fields, but in order to achieve good beam-spot resolution the beamline must be aligned to the stray DC fields in the laboratory. The relative thickness of the optical elements compared to the curvature of the beam in such fields causes aberration where the beam axis differs from the optical axis of the lens system. In this paper numerical ray tracing has been used to study the influence of stray DC magnetic fields on beam resolution at the sub-micron level using typical field strengths for the Earth's magnetic field as a case study.



## 1. Introduction

Stray DC fields in the microbeam laboratory environment are unavoidable. To achieve good beam-spot resolution the optical elements of the beamline must be aligned to the path taken by the beam in the presence of such stray DC fields, otherwise the particles will enter the lens system off-axis, causing large parasitic aberrations. A study by Jamieson has shown that stray DC fields arising from misalignment of the stainless steel beam-tube passing through the bore of the magnetic quadrupole lenses of the Melbourne microprobe leads to significant sextupole aberration [3]. Such a field may be cancelled by correct alignment of the beam-tube and lenses. However, the beam may be influenced by other stray DC fields in the laboratory causing curvature of the beam path, making alignment of such a relatively long beam-tube impossible.

The Earth generates a magnetic field in the order of 50 μT, and with common microbeam lengths greater than 5 m this results in a deflection in the order of millimetres. The established experimental technique of "dipole minimization", as described by Grime and Watt [2], is to align the optical elements of the focused system to the true path of the ions through any stray fields, thus ensuring that the ions pass through the optical centre of each element, minimizing aberrations caused by misalignment of the beam and focussing system. However, in the presence of a stray field, the alignment procedure is only valid for the magnetic rigidity of ions for which the beamline was aligned.

The influence of stray AC magnetic fields is far more serious than that of DC magnetic fields, but this has been well addressed by Jamieson [3].

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## 2. The magnetic field of the Earth

The National Geophysical Data Centre, USA [4] provides values for the strength of the Earth's magnetic field in London, UK. These values are the closest available to the University of Surrey Ion Beam Centre, and as such should be a good approximations to field strengths in Surrey, UK.

The microbeam system used for simulation in this paper uses three magnetic quadrupole lenses in an Oxford Triplet geometry [6]. The beamline is 6.367 m in total length from object to image planes.

For this simulation, the beamline is orientated directly from east to west, and a 2.5 MeV beam of protons will receive deflections of −3.96 mm and 1.7 mm in the $x$–$z$ and $y$–$z$ axis respectively due to the Earth's magnetic field.

To model the Earth's magnetic field, a magnetic dipole with a pole tip field of 48,578 nT has been inserted into the simulation of the Oxford Triplet, and rotated by 1.6 rad about the $y$ axis, and 0.41 rad about the $x$ axis giving field strengths equal to those shown in Table 1.

This paper studies three concerns arising from the influence of stray DC magnetic fields on a beamline.

- The first concern is aberration arising from the imperfection in the alignment when relatively thick quadrupole lenses are aligned to the curved path taken by the beam in the presence of stray DC magnetic fields.
- The second concern is whether chromatic aberration increases due to the changing path of a chromatically spread beam in a DC magnetic field.
- The third concern is the degradation of focussing quality of the microprobe when ions of a different magnetic rigidity are used to that for which the optical elements of the beamline were aligned to.

**Table 1**
The magnetic field of the Earth in London, UK [4].

| Latitude | 51° 28′ 48″ |
|---|---|
| Longitude | − 10′ 12″ |
| Elevation | 0.00 m |
| Declination | − 1° 54′ |
| Inclination | 66° 28′ |
| Horizontal intensity | 19,394.4 nT |
| North component | 19,383.7 nT |
| East component | −643.5 nT |
| Vertical component (Down +ve) | 44,538.7 nT |
| Total field | 48,578.2 nT |

The third concern may be significant for experiments where a beam spot in the 10 nm range is required. The beam alignment process can take up to 30 min in duration for beam-spot dimensions in 1 μm range [2], and considerably longer to achieve sub-micron performance. Such a delay may be inconvenient to experiments requiring an change of ion rigidities between experimental runs. This is very relevant to the proton beam writing technique which often requires a range of ion rigidities to make multiple depth three dimensional structures.

## 3. Simulation

Simulation of the influence of stray DC magnetic fields using numerical raytracing is achieved by replicating experimental practice for aligning the centre of optical elements to the new beam axis. This can be achieved in the following steps.

1. Excitation of all active elements in the simulation are set to zero.
2. A magnetic dipole representing the stray field is added to the simulation, and excited.
3. A para-axial ray is traced, and the ray coordinates are recorded of as the ray passes through the centre of each optical element, including object and collimator apertures, and the final position at the image plane is recorded.
4. The pre-object path of the particle is adjusted such that the particle passes through both object and collimating apertures despite the influence of the stay field.
5. The centre and tilt of all optical elements in the simulation are adjusted to the recorded positions of the paraxial ray.
6. The excitations of active elements in the simulation are optimised to give a focus at the new image position.

"Active" elements are those elements which alter the particle trajectory by means of an electrostatic or magnetic field. In this case they refer to the quadrupole lenses.

### *3.1. Aberration due to imperfect alignment in presence of Stray DC field*

Typical magnetic quadrupole lenses used in sub-micron microprobe systems are between 50 mm and 100 mm in length [1]. The curved path of the ions in the magnetic field mean that it is impossible for the microbeam operator to align a lens to the path of the ions over the whole length of the lens, although the deviation from perfect alignment is small, aberrations are introduced into the final image. The sensitivity of various systems to misalignment of individual lenses has been thoroughly addressed by Grime and Watt [2], however, no study has been made of the cumulative misalignment of several lenses as may be found in the presence of a stray DC field (see Table 2).

Grime and Watt [2] recommend the method of "dipole minimization" for alignment of optical elements in the presence of stray fields. This process requires the microbeam operator to form line foci in each plane consecutively with each magnetic quadrupole lens, at each stage adjusting the alignment of the lens to minimize any steering of the beam spot away from the observed beam axis. However, it is impossible for the microbeam operator to distinguish between tilt and translation misalignment since both are first order aberrations, causing a displacement of the image. The final alignment therefore may be some imperfect combination of tilt and translation that happens to give a beam spot that appears to coincide with the beam axis. The dipole minimization method only provides for the correction of translation misalignment, with any tilt corrected using a straight-edge across all lenses prior to the procedure. Therefore, the tilt-alignment show in this section is presented as a best-possible case. However this tilt-alignment is unlikely to be necessary to reach the required tolerances for sub-micron beam spots in most microbeam lens configurations.

The procedure for simulation detailed above aligns the tilt and translation of each optical element in the simulation exactly to the beam axis at the geometric centre of each element. Therefore any aberrations arising from misalignment are due to the curved path of the beam in the stray DC magnetic field. Fig. 1 shows a comparison between point spread functions of the beamline with and without the presence of the Earth's magnetic field.

The first order effect of such misalignment is evident in the slight offset of the centre of the point spread function shown in Fig. 1b.

Fig. 1c and d shows *difference* point spread functions for beamline aligned in translation, and translation–tilt respectively. The *difference* point spread function is generated by subtracting the aberration coefficients calculated in the absence of stray fields from those calculated with the aligned matrix, leaving a polynomial of difference terms. This is shown in Table 3.

The degradation in focus quality due to imperfect alignment is characterised by an increase in 2nd and 4th order aberration terms in both planes, $\langle x|\theta^2\rangle$,$\langle x|\phi^2\rangle$, $\langle y|\phi^2\rangle$,$\langle y|\theta^2\rangle$, particularly the cross-coupling terms, $\langle y|\theta\phi\rangle$, $\langle y|\theta^3\phi\rangle$, $\langle y|\theta\phi^3\rangle$.

The aberration $\langle y|\theta\phi\rangle$ is by far the most dominant from the set of misalignment and chromatic aberrations introduced by the stray field, and can be reduced by a factor of two by correctly aligning each element in tilt as well as translation. Fig. 1c and d shows that

**Table 2**
Matrix of aberration coefficients for Oxford Triplet without stray DC field[a].

| | $x$ | $y$ | $\theta$ | $\phi$ |
|---|---|---|---|---|
| *Aberration matrix: units: μm/mrads* | | | | |
| $\theta$ | −0.025 | | 82.4 | |
| $\phi$ | | 0.631 | | −31.5 |
| $\theta\delta$ | −396 | | −3.95 | |
| $\phi\delta$ | | 863 | | 4.28 |
| $\theta^3$ | 725 | | 4.83 | |
| $\theta^2\phi$ | | −3.96E+03 | | −19.9 |
| $\theta\phi^2$ | 1.51E+03 | | 13 | |
| $\theta\delta^2$ | 10.2 | | 0.0791 | |
| $\phi^3$ | | −4.8E+03 | | −23.5 |
| $\phi\delta^2$ | | −21.4 | | −0.11 |

| Variable | Order | Range | Mean |
|---|---|---|---|
| $\theta$ | 3 | 0.1 | 0 |
| $\phi$ | 3 | 0.1 | 0 |
| $\delta$ | 2 | 0.002 | 0 |

[a] Aberration coefficients of magnitude less than $1 \times 10^{-3}$ μm/mrad/% have not been shown due to their negligible influence on the ray coordinate in the image plane.

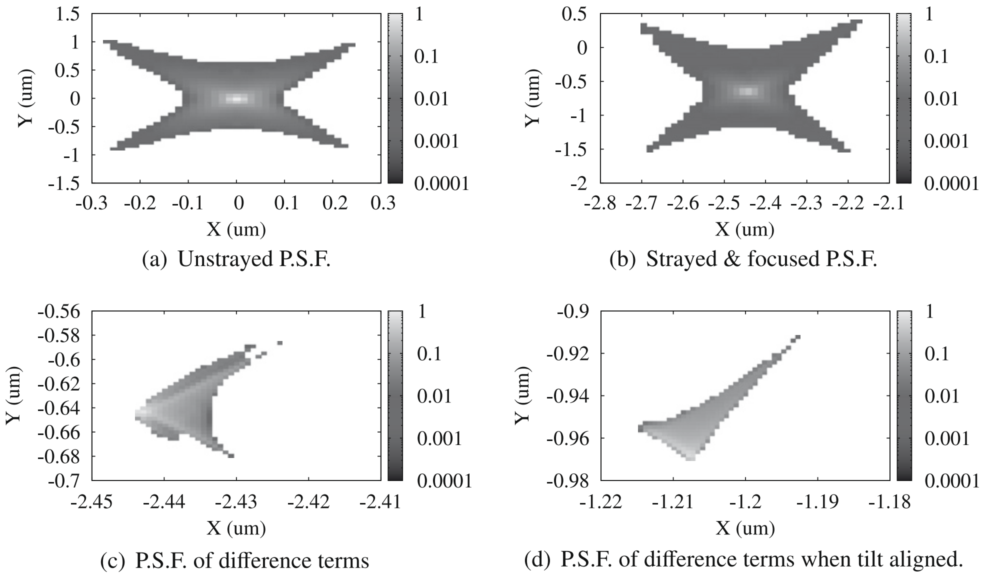


**Fig. 1.** Point spread functions ($\theta, \phi = 0.1$ mrad, $\delta = 2 \times 10^{-3}\%$) for alignment procedures to stray DC field.

**Table 3**
Difference Matrix of aberration coefficients for comparison of beamline with and without stray DC field, when optical elements have been aligned in translation to the path of the 2.5 MeV H+ beam in the stray DC field.[a]

| | $x$ | $y$ | $\theta$ | $\phi$ |
|---|---|---|---|---|
| *Aberration matrix: units: $\mu$m/mrad/%* | | | | |
| | −2.44 | −0.644 | −0.0173 | |
| $\theta$ | 0.0789 | −0.0233 | | |
| $\phi$ | | −0.146 | | |
| $\delta$ | −0.238 | −0.767 | 0.474 | 0.077 |
| $\theta^2$ | 2.24 | 3.2 | 0.0365 | 0.0119 |
| $\theta\phi$ | −2.44 | −20.5 | −0.0115 | −0.1 |
| $\theta\delta$ | 0.0212 | 0.0979 | | |
| $\phi^2$ | 3.93 | 4.29 | 0.0517 | 0.0183 |
| $\phi\delta$ | −0.0312 | −0.119 | | |
| $\delta^2$ | −2.29 | −2.21 | −0.0278 | −0.0118 |
| $\theta^3$ | 0.0137 | −0.0337 | | |
| $\theta^2\phi$ | | −0.0501 | | |
| $\theta^2\delta$ | 12.5 | 10 | 0.0826 | 0.0505 |
| $\theta\phi^2$ | 0.0203 | −0.0564 | | |
| $\theta\phi\delta$ | −7.58 | −45 | −0.0657 | −0.226 |
| $\theta\delta^2$ | 0.0821 | 0.113 | | |
| $\phi^3$ | −0.012 | −0.0633 | | |
| $\phi^2\delta$ | 8.54 | 36.8 | 0.0737 | 0.181 |
| $\phi\delta^2$ | −0.0426 | −0.216 | | |

| Variable | Order | Range | Mean |
|---|---|---|---|
| $\theta$ | 3 | 0.1 | 0 |
| $\phi$ | 3 | 0.1 | 0 |
| $\delta$ | 2 | 0.002 | 0 |

[a] Aberration coefficients of magnitude less than $1 \times 10^{-3}$ μm/mrad/% have not been shown due to their negligible influence on the ray coordinate in the image plane.

**Table 4**
Difference matrix of aberration coefficients for comparison of beamline in stray DC field with translation and translation–tilt alignment.[a]

| | $x$ | $y$ | $\theta$ | $\phi$ |
|---|---|---|---|---|
| *Aberration matrix: units: $\mu$m/mrads/%* | | | | |
| | −1.21 | −0.965 | | 0.0134 |
| $\theta$ | 0.0608 | −0.0222 | | |
| $\phi$ | | −0.157 | | |
| $\delta$ | −0.31 | −0.874 | 0.473 | 0.0764 |
| $\theta^2$ | 1.07 | 4.79 | 0.0181 | 0.0178 |
| $\theta\phi$ | −3.65 | −10.2 | −0.0165 | −0.0483 |
| $\theta\delta$ | 0.0115 | 0.0898 | | |
| $\phi^2$ | 1.96 | 6.35 | 0.0259 | 0.027 |
| $\phi\delta$ | −0.0278 | −0.0693 | | |
| $\delta^2$ | −2.29 | −2.2 | −0.0277 | −0.0117 |
| $\theta^3$ | 0.0106 | −0.0349 | | |
| $\theta^2\phi$ | | −0.0342 | | |
| $\theta^2\delta$ | 12.6 | 9.92 | 0.0832 | 0.0501 |
| $\theta\phi^2$ | 0.0143 | −0.0601 | | |
| $\theta\phi\delta$ | −7.51 | −45.4 | −0.0652 | −0.228 |
| $\theta\delta^2$ | 0.0824 | 0.113 | | |
| $\phi^3$ | −0.0128 | −0.0412 | | |
| $\phi^2\delta$ | 8.63 | 36.7 | 0.0748 | 0.18 |
| $\phi\delta^2$ | −0.0427 | −0.218 | | |

| Variable | Order | Range | Mean |
|---|---|---|---|
| $\theta$ | 3 | 0.1 | 0 |
| $\phi$ | 3 | 0.1 | 0 |
| $\delta$ | 2 | 0.002 | 0 |

[a] Aberration coefficients of magnitude less than $1 \times 10^{-3}$ μm/mrad/% have not been shown due to their negligible influence on the ray coordinate in the image plane.

the total contribution to the point spread function of the Oxford Triplet system due to stray field misalignment, for 2.5 MeV protons with angular divergence of 0.05 mrad is less than 5% of the point spread function in the absence of stray DC fields.

### 3.2. Increased chromatic aberration

Table 3 shows that chromatic aberration of the beamline is increased beyond the values given in the absence of stray fields due to not only to over-focussing of the lens elements, but an aberration introduced by the angular spread arising from dispersion of the beam in the Earth's magnetic field. This leads to a beam that is spatially spread within the lenses, causing slight misalignments for particles not of the mean energy. However this effect is a negligible concern for microbeams.

The terminal voltage in 2MV Tandetron accelerator at the University of Surrey Ion Beam Centre is specified to be stable to better than 50 V [5]. For the Oxford Triplet lens geometry, and a

**Table 5**
Displacement and Broadening of the image due to change in magnetic rigidity of ion from alignment rigidity (0.228 Tm).

| Rigidity (Tm) | 0.144 | 0.176 | 0.204 | 0.228 | 0.249 | 0.322 |
|---|---|---|---|---|---|---|
| Mass (amu) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 4.0 |
| Charge (eV) | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 2.0 |
| Rigidity difference (Tm) | −0.0837 | −0.0513 | −0.0240 | 0.0 | 0.0217 | 0.0943 |
| Energy (MeV) | 1.0 | 1.5 | 2.0 | 2.5 | 3.0 | 2.5 |
| Image displacement $X$ (μm) | 22.02 | 11.22 | 4.56 | 0.0 | −3.234 | −11.04 |
| Image displacement $Y$ (μm) | 31.48 | 16.07 | 6.54 | 0.0 | −4.834 | −15.83 |
| Broadening $X$ (μm) | 1.042 | 0.334 | 0.0778 | 0.0 | 0.0749 | 0.154 |
| Broadening $Y$ (μm) | 4.052 | 1.52 | 0.494 | 0.0 | 0.354 | 0.693 |
| Point spread function figure | 2a | 2b | 2c | 2d | 2e | 2f |

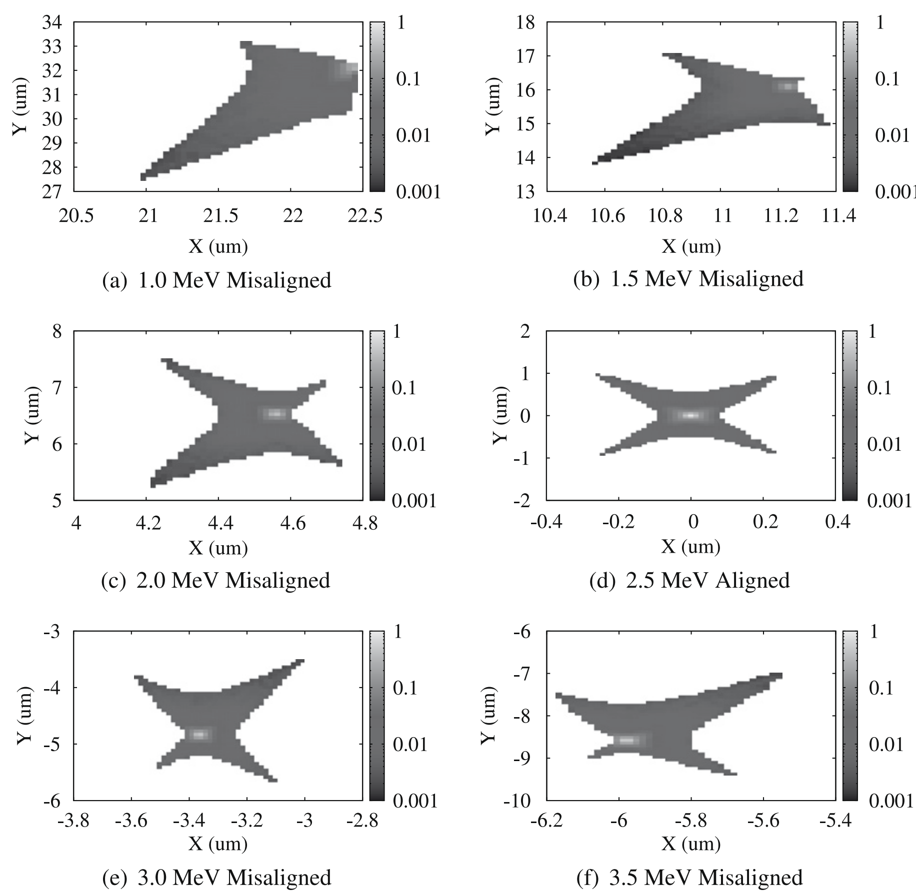


**Fig. 2.** Point spread function ($\theta, \phi = 0.1$ mrad, $\delta = 2 \times 10^{-3}$%) when beamline is refocused but not re-aligned.

2.5 MeV $H^+$ beam from the Surrey 2MV Tandetron, the increase in chromatic aberration when aligned to the Earth's magnetic field is five orders of magnitude less than the total magnitude of chromatic aberration in the absence of stray fields (see Table 4).

### 3.3. Focussing performance degradation when changing beam energy

In practice, when changing beam energy the microbeam operator will experimentally optimise beam current at the new beam energy by using any steering elements available before the object aperture such that the beam direction is matched to the acceptance defined by object and collimator apertures. This corrects for the transverse influence of the stray field before the collimating aperture, however this pre-object alignment can only correct the transverse offset of the beam to the beam geometric axis such that it arrives at the correct location in the collimating plane. The stray field will cause the beam to travel in a curved path, causing a angular deviation from the geometric axis leaving the collimating aperture.

Thus, the direction and radius of curvature of the beam leaving the collimating plane changes with magnetic rigidity of the beam, causing an effective misalignment of post-collimator elements. In two-stage systems this may cause considerable misalignment due to the "early" position of the collimating aperture in the first stage – causing a large distance from collimating aperture to image plane.

There is strong third order aberration associated with path changes due to variation of magnetic rigidity, as would be expected from high third order angular response of the Oxford Triplet lens system. The aberration terms $\langle x|\theta\phi\chi\rangle$,$\langle y|\theta\phi\chi\rangle$ cause a strong parasitic broadening effect on the focused image, where $\chi$ is used to denote the magnetic rigidity of the ions.

Displacement effects may be solved relatively easily by the use of fiducial marks on the sample holder, to provide accurate positions (requiring a recalibration for each change of rigidity). Beam broadening effects are more severe, and can only be corrected by re-alignment, or by reduction of the angular divergence of the beam, causing a significant reduction in beam current transmitted to the target.

Table 5 shows the magnitude of broadening and displacement effects for the Oxford Triplet lens geometry due to the stray DC field for a range of ion rigidities for the Oxford Triplet beamline aligned for a beam of 2.5 MeV protons.

Fig. 2 shows the point spread functions for a range of $H^+$ beam energies from 1.0 MeV to 3.5 MeV for a system aligned at 2.5 MeV.

## 4. Conclusion

It is clear that stray DC fields in a microbeam environment do produce intrinsic and chromatic beam aberrations, but that the magnitude of these is relatively small in comparison to spherical aberration when optical elements are correctly aligned to the true path of the beam. A more concerning effect is focus degradation when changing ion rigidity. This degradation is important to the proton beam writing community who commonly use multiple ion energies to “write” three dimensional structures. A point of note is that higher ion rigidities particles will receive less deflection from the Earth’s magnetic field, and thus aberrations introduced from lens misalignment will be reduced.

A further consideration relating to beamline construction is that mono-block lens assemblies will never achieve perfect alignment due to the inability to align lenses separately, and this may make them unsuitable for nanobeam performance systems, depending on the lens geometry used, although a possible advantage is that the re-alignment process of the entire assembly is far simpler and quicker than that of separated lenses.

Problems with stray DC and AC magnetic fields can be greatly alleviated by using mu-metal to shield the beamline from such fields. To shield a beamline effectively any long drift lengths should be shielded particularly between the object and collimator apertures. The influence of stray fields are most damaging in the vicinity of the object aperture due to the lever effect of any deflections introduced to the beam. Mu-metal shielding may prove critical to achieving beam-spot dimensions in the nanometre range, depending on the geometry of the lens system used.

## Acknowledgements

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