# FOCUSING OF A RELATIVISTIC ELECTRON BEAM WITH A MICROFABRICATED QUADRUPOLE MAGNET

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## ABSTRACT

We show in this work the first reported results of relativistic electron beam focusing using a microfabricated device. The application of microfabrication to beam physics responds to a need in the particle accelerator community for miniature, economical components that can be used in a range of diverse applications ranging from nanofabrication to electron beam therapy. Quadrupole magnets, like the device described in this paper, are essential parts of any accelerator. We demonstrate beam focusing of a relativistic (3.2 MeV) electron beam, and further show that vertical steering errors can be corrected by modifying the current in the device instead of re-alignment. We also present magnetic field data that show better than 3% agreement with simulation.

## KEYWORDS

Particle accelerator, magnetism, electron optics, quadrupole

## INTRODUCTION

### Motivation

This work is centered around miniaturizing the magnetic optics used to steer and focus relativistic electron beams. Electron beams are electron currents in free space and are used in medical applications (electron beam therapy, sterilization), nanofabrication, synchrotrons, and many others [1]. The two main components used in electron beam optics are dipole and quadrupole magnets. Whereas traditional optics use mirrors and lenses to steer and focus light, magnetic optics use the Lorentz force to steer and focus electron beams. Dipole magnetic fields feature a homogenous field for steering, whereas quadrupole magnets use quadrupolar fields, which vary linearly in space, for focusing. Electron beams inherently diverge due to space charge effects and non-zero beam emittance, so quadrupoles are needed to periodically refocus the beam. Quadrupoles focus in one transverse dimension and defocus in the other, so several quadrupoles, with fields rotated by 90 degrees, are needed to focus the beam in both dimensions simultaneously.

We present here *the first microfabricated planar quadrupole* (MPQ), whose distinguishing feature is an arbitrarily long magnetic length limited only by wafer size, shown in Fig. 1. The MPQ was inspired by the so-called "Panofsky" style of macro-scale quadrupoles [2]. With more than an order of magnitude reduction in footprint compared to conventional electromagnet quadrupoles, this device is well-suited for integration in upcoming compact electron accelerators.

### Quadrupole Mechanism

A quadrupole is characterized by its *transverse gradient*, or the magnetic field gradient produced in the transverse plane, and its *effective magnetic length*, which is the length over which the gradient is maintained. The focusing strength of the quadrupole is dictated by the *integrated gradient*, which is the transverse gradient integrated along the length of the quadrupole. Large-scale conventional quadrupoles produce 1-10 T integrated gradients. Our group previously showed a miniature quadrupole [3] with an integrated gradient of 0.025 T. Photonic crystals have been used to make microscale quadrupoles [4], but can only focus relatively low-energy electron beams (< 35 MeV). The MPQ presented here showed a maximum integrated gradient of 0.044 T. The integrated gradient was limited in this first demonstration by low currents (because of the power supply limits) and a non-optimized geometry. Fixing these issues would improve the integrated gradient by one to two orders of magnitude.

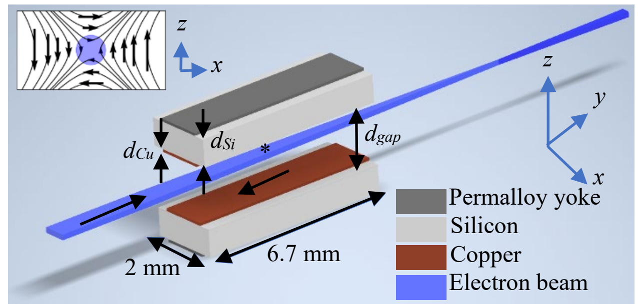


*Figure 1: Schematic of one MPQ focusing an electron beam. The current direction is same in both copper sheets (-y direction) as shown by the arrow. The beam direction is also indicated by an arrow in the +y direction. The inset shows the electron beam cross section superimposed on the quadrupole field at the origin ("*").*

## DESIGN

The MPQs are fabricated by electroplating 2 mm wide, 50 um-thick copper traces on the front and 2 mm wide, 50 um-thick permalloy on the back of a 500 µm-thick silicon wafer (Fig. 2a). The wafer is diced and the MPQs are mounted on PCBs and aluminum fixtures such that the two chips face each other, as shown in Fig. 2b. The MPQ copper carries current (10s A) to generate the magnetic field, and the permalloy guides the magnetic flux to maximize the transverse gradient. The standoff distance between MPQ halves is set with spacers.

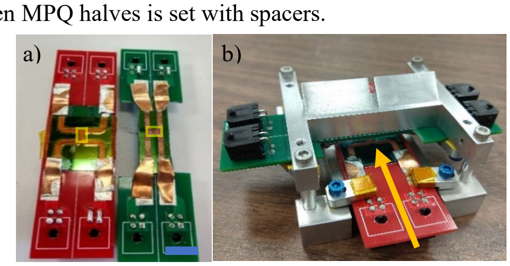


*Figure 2: a) MPQ devices, copper side up, mounted on a PCB. Blue scale bar is 1 cm. The active areas from Fig 1 are located at the yellow boxes. b) fully assembled MPQ device with beam direction shown in yellow.*

Assuming the length is much greater than other dimensions and the yoke permeability is large and non-saturating, magnetic circuit analysis predicts the gradient of this device to be

$$dB_z/dx = \mu_0 J \,/\, (\, 1 + d_{gap}/(2d_{Cu}) + d_{Si}/d_{Cu}\,) \qquad (1)$$

where $dB_z/dx$ is the gradient, $\mu_0$ is the permeability of free space, $J$ is the current density in the copper sheets, and $d_{gap}$, $d_{Si}$, $d_{Cu}$ are the gap distance between MPQ halves, silicon thickness, and copper sheet thickness respectively (Fig. 1). This scaling law shows that small gaps and small (large) thicknesses for silicon (copper and permalloy) are beneficial to increase the gradient. These considerations informed the design, in tandem with electron beam considerations, fabrication restraints, and simulation.

## RESULTS

### Hall Probe Magnetic Field Measurement

We first used a Hall probe to map the magnetic field in the MPQ. The gap was set to 5.6 mm to accommodate the Hall probe thickness. We measured $dB_z/dx$, the transverse gradient, along the *y* axis, which is the direction the electron beam travels. The experimental results match magnetostatic simulations from RADIA within 3%, which is shown in Fig. 3.

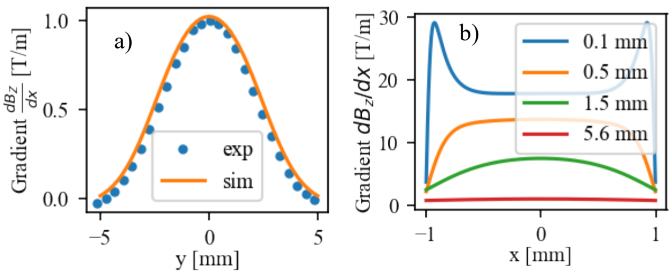


*Figure 3: a) Comparison of experimentally measured and simulated gradient ($dB_z/dx$) along y-axis at x = z = 0 at a current of 20 A (2E+8 A/m$^2$ current density) and 5.6 mm gap. b) RADIA simulations of the transverse gradient ($dB_z/dx$ along the x direction at y = z = 0) at different gaps. The gradient becomes larger and more uniform around x=0 with decreasing gap.*

### Relativistic Electron Beamline Measurements

Focusing of a relativistic electron beam was performed at the UCLA Pegasus beamline [5]. The electron bunch is created in the photoinjector, accelerated to a kinetic energy of 3.2 MeV (relativistic factor $\gamma$=7.24), focused by the MPQ, then imaged on a screen 0.5 m downstream. The MPQ gap was set to 1.5 mm. For the first experiment the current in both MPQ halves was the same. The beam was fully focused at a current of 22 A to 335 µm in the *x* dimension, shown in Fig. 4. As expected, the *z* beam size continually increased as the current magnitude increased. At 22 A the MPQ magnetic field gradient is around 5 T/m with an integrated gradient of 0.024 T; the integrated gradient at 40 A is 0.044 T, with a focal length of 279 mm.

In addition to beam focusing, the test also revealed a significant beam displacement in the *z* direction. We found experimentally that the displacement can be compensated and eliminated by using approximately four times more current in the top MPQ half. This effectively superimposes an additional $B_x$ dipole component over the pure quadrupole field which counteracts other sources of vertical deflection. We show the results of both uncompensated and compensated experiments in Fig. 4. The cause of the deflection is still under investigation. We note that in both experiments the *x* displacement was close to zero, which means that the MPQ was well-centered in the *x* direction, and the beam over-filled the MPQ aperture, therefore automatically satisfying *z* alignment.

## CONCLUSIONS

We have demonstrated focusing of a relativistic electron beam with a microfabricated device for the first time. We showed that vertical steering errors can be compensated by using different currents in the MPQ top and bottom halves. The measured magnetic field is within 3% of the simulated field. This work is an important step towards microfabricated-enabled accelerator-on-a-chip devices, which could significantly enhance access to relativistic electron beams for research and industrial applications.

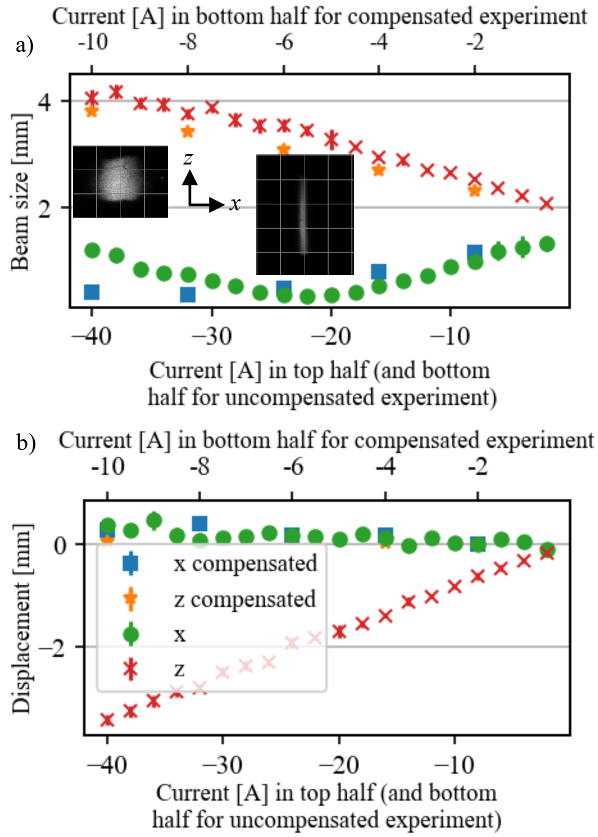


*Figure 4: Current compensation preserves beam focusing while mitigating beam shift. Legend in (b) is the same for both plots. a) Beam diameter as a function of current. The current is directed in the -y direction (see Fig. 1). The current in both MPQ halves corresponds to the bottom axis for the uncompensated experiment. For the compensated experiments, the top x-axis shows the current in the bottom half. Images show the unfocused (left) and focused (right) beam. The grid boxes are 1 mm by 1 mm. b) net beam deflection as a function of current with the same axes convention for uncompensated/compensated experiments as (a). Error bars denote one standard deviation of at least five measurements.*

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