Microscale Magnetic Flux Sources for Electron Beam Manipulation

Rob Candler
Department of Electrical Engineering
California NanoSystems Institute
UCLA
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Micromachined Electromagnets

- L ~ 10s nH – 10s μH
- C ~ 1 pF
- R ~ 10 mΩ

NiFe core
- $B_{\text{sat}}$ ~ 1T
- $\mu_{\text{rel}}$ ~ 8000

Soft magnet core
Windings

Current

$\vec{B}$

Batch-fabricated Electromagnets
Quadrupole Focusing

- Electron beam focusing
- Each quadrupole focuses in x or y, multiple quadrupoles used in concert

FIG. 7. (Color) Standard triplet design for a symmetric focus.

Triplet focusing configuration

Rosenzweig et al., PRST-AB 2005
Quadrupole Focusing - Scaling

\[ B_{sat} \sim \text{Constant} \]

\[ \nabla B \propto \frac{B_{sat}}{x_0} \]

\[ B_{sat} \equiv \text{Saturation magnetization} \]
Particle Focusing with Miniature Magnetics

<table>
<thead>
<tr>
<th>Currently Available</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
</tr>
<tr>
<td>Permanent Magnet Quadrupole</td>
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</table>

<table>
<thead>
<tr>
<th>$\nabla B$</th>
<th>560 T/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner diameter</td>
<td>5 mm</td>
</tr>
<tr>
<td>Tuning</td>
<td>Axial translation of magnets</td>
</tr>
</tbody>
</table>

Permanent magnet wedges

Rosenzweig et al., 2005
Particle Focusing with Miniature Magnetics

<table>
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<tr>
<th>Currently Available</th>
<th>Future</th>
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<tbody>
<tr>
<td>Technology</td>
<td>μ machined Electromagnets</td>
</tr>
<tr>
<td>Permanent Magnet Quadrupole</td>
<td></td>
</tr>
<tr>
<td>∇B</td>
<td>&gt;3,000 T/m</td>
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<tr>
<td>Inner diameter</td>
<td>200 μm</td>
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<tr>
<td>Tuning</td>
<td>Electromagnet</td>
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<tr>
<td>Axial translation of magnets</td>
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</tbody>
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Top metal

Vias

200 μm
Simulations: Quadrupole Geometry

- In mid-plane, used for radial field variation
- Along beam axis, used for longitudinal and radial field variation

Bryce Jacobson (RadiaBeam)
Quadrupole 3D Sims

Bryce Jacobson (RadiaBeam)
Workshop on Physics and Applications of High Brightness Beams

Quadrupole 3D Sims

Transverse field variation along beam axis, $B_y(z)$, shown along several displaced lines.

FWHM of longitudinal profile ~ 180 um; reasonable magnetic length for quadrupoles.

Bryce Jacobson (RadiaBeam)
Quadrupole 3D Sims

Transverse and magnitude of field in midplane, $B_x(x,y,0)$, $B_y(x,y,0)$, and $\text{Mag}_B(x,y,0)$, from center of quadrupole bore radially outward.

Bryce Jacobson (RadiaBeam)
Micromachined Undulator
Undulator structure

Yoke
Windings
Via
Gap
Undulator Scaling for FELs

- Radiation wavelength scales directly with $\lambda_r \propto \lambda_u$
- Undulator parameter scales with $K \propto \lambda_u$
- Gain length scales with $L \propto \lambda_u^{1/6}$
- Pierce parameter scales with $\rho \propto \lambda_u^{5/6}$ (assuming constant $\lambda_r$)

Small $K$ ($\sim 0.01$) assumed

Other challenges include wakefields and space charge effects
Undulator Simulations

Fabrication

- Microundulator shown
- Process adapted for quadrupoles (hole etched through quad)

Electromagnets

200 μm
Fabrication

(1) Cu in Si trench Damascene process
- Etch trench with DRIE
- Isolate trenches with thermal oxidation
- Sputter plating seed
- Fill trenches with electroplated copper
- Planarize with CMP
Fabrication

(2) Electromagnet yoke electroplating

- Isolate windings (PECVD nitride)
- Sputter plating seed
- Pattern plating mold
- Electroplate yoke
- CMP yoke flat
- Strip mold and seed
Fabrication

(2) Electromagnet yoke electroplating
- Isolate windings (PECVD nitride)
- Sputter plating seed
- Pattern plating mold
- Electroplate yoke
- CMP yoke flat
- Strip mold and seed
Electroplated Thin Film Magnetic Materials

**Permalloy (NiFe 80/20)**

- **Relative Permeability**
  - \( \mu_{\text{rel}} \approx 8000 \)

- Thickness up to ~50 μm (low stress)

- **Bsat** ~ 1 T

Judy et al., Hilton Head Workshop 2010

**CoNiFe**

(under development, DARPA N66001-12-1-4209)

- **Relative Permeability**
  - \( \mu_{\text{rel}} \approx 600 \)

- **Bsat** ~ 2 T

Rob Candler’s lab & Magzor
Fabrication

(3) Via & waveguide
- Isolate yoke (PECVD)
- SU8 lithography optimized for low film stress
(3) Via & waveguide

- Isolate yoke (PECVD)
- SU8 lithography optimized for low film stress
(4) Top winding process

- RIE etch oxide in vias
- Sputter plating seed
- Pattern winding plating mold in KMPR
- Electroplate gold from K(AuCN)₂ bath
- Strip mold and seed
Fabrication

Top view

Windings (top)
Quadrupoles (recently fabricated)
Characterization Plans

- Electrical
- Magnetic
  - MFM - Magnetic Force Microscopy
  - Pulsed wire
  - NMR – Nuclear Magnetic Resonance
- Optical
  - PEGASUS beamline
Electrical Characterization

- Impedance Analyzer
- DUT
- Probe Station
- PC
Magnetic: Magnetic Force Microscopy

http://jazyky.mluvmespolu.eu/
Magnetic: Pulsed Wire Measurement for Undulator
Magnetic Characterization (NMR)

Water filled 100 µm capillary NMR probe swept down the undulator gap
Optical Characterization - Undulators

Experiment vacuum chamber with optical breadboard, 4-axis positioning, water cooling, high power and general purpose interconnects

Measuring 431 nm undulator output and electron beam energy modulation
Optical Characterization - Undulator

Simulations

Photons in visible spectrum expected from Pegasus beamline
MEMS-Quads test at UCLA Pegasus

- **Energy**: 12 MeV
- **Charge**: 1 pC
- **Emittance**: 20 nm
- **Energy spread**: 0.05%
- **Bunch length**: 200 fs (10 fs compressed)

At screen (simulation)

**Quad off**

**Quad on 1000 T/m**
Summary

• Micromachined quadrupoles promise $kT/m$ field gradient
  – Testing underway

• Micromachined undulators enable miniaturization of period to 100 μm
  – Initial tests planned on 10 MeV beamline
Thank You