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Micro Penning Traps for Continuous Magnetic Field Monitoring in High Radiation Environments

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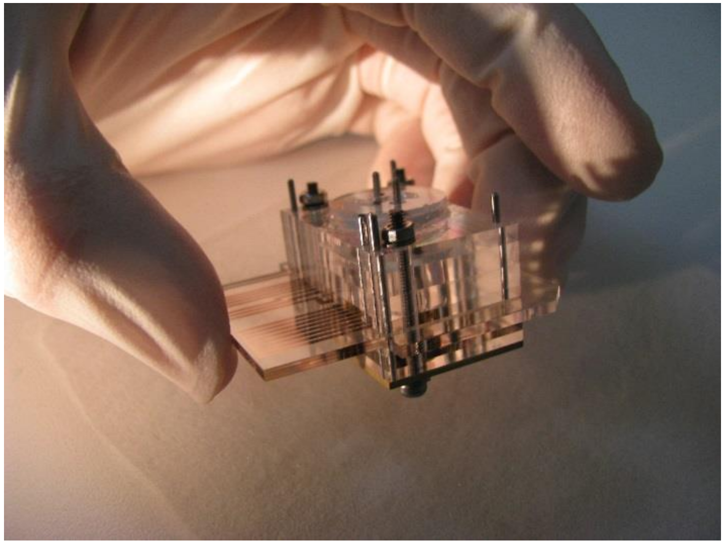

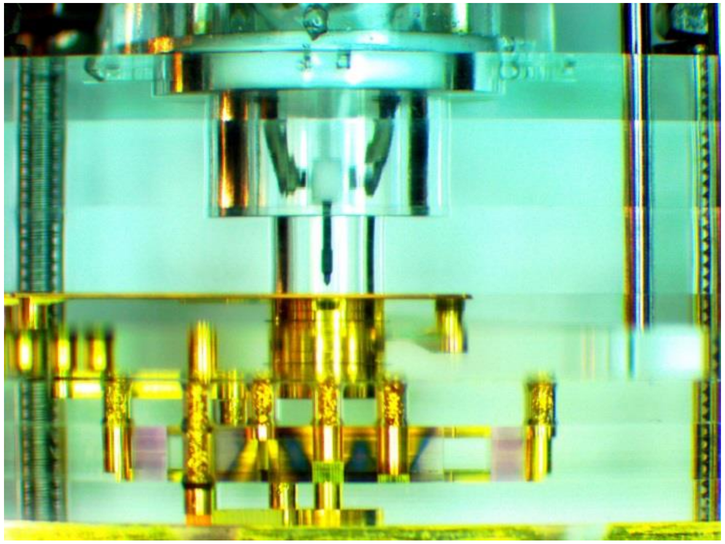

Collaborators

Michigan State University, Facility for Rare Isotope Beams

- Dr. Ryan Ringle, Dr. Kerim Gulyuz, Dr. David Lincoln, Dr. Georg Bollen

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- Mr. Chris Schenck, Dr. Philippe Bado, Dr. Ali Said

Outline

- Need for radiation–resistant magnetic field probes
- Measuring magnetic field with Penning trap
- The MSU minitrap design
- Three-dimensional precision machining of ion microtraps made out of fused silica glass
- The microtrap magnetometer

Need for radiation–resistant, continuous monitoring magnetometer

- Next generation rare isotope beam facilities and accelerators will operate at increased radiation levels.

- Existing semiconductor based probes, nmr probes, have limited lifetime at current radiation levels of operational facilities.

- Magnetic field probes needed at multiple locations in the beam line with different measurement precision and electronic shielding requirements. (separators and spectrometers; 1 part in 10^6)

- Continuous monitoring to detect short-term, non-linear fluctuations in the magnetic field. Efficient use of beam time -> Increase precision and sensitivity.

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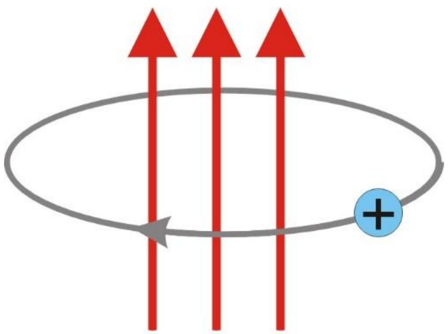
Measuring Magnetic Field with a Penning Trap

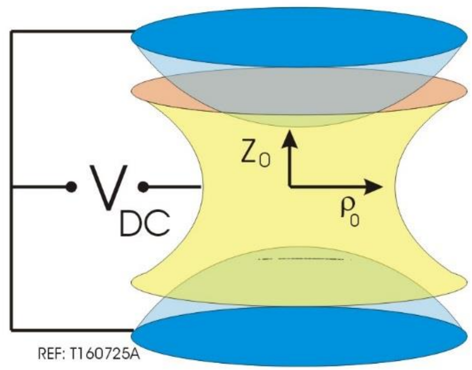
Uniform B-field



$$\omega_c = \frac{q}{m} B$$

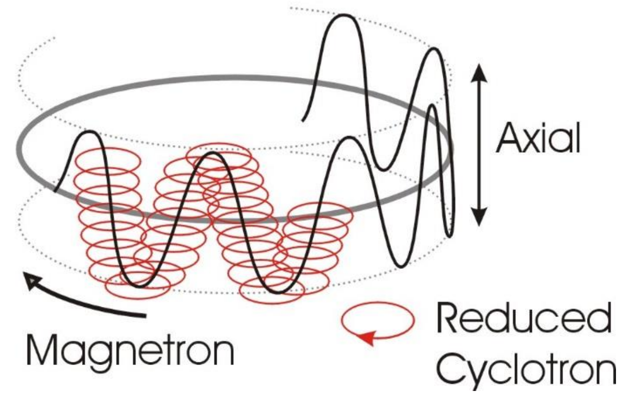
ω_c = cyclotron frequency
q = ion charge
m = ion mass
B = magnetic field

Quadrupole E-field



$$d = \sqrt{\frac{\rho_0^{\,2}}{4} + \frac{z_0^{\,2}}{2}}$$

3 Normal Modes



$$\omega_z = \sqrt{\frac{qV_{DC}}{md^2}}$$

$$\omega_{\pm} = \frac{\omega_c}{2} \pm \sqrt{\frac{\omega_c^{\,2}}{4} - \frac{\omega_z^{\,2}}{2}}$$

Normal frequency hierarchy

$$\omega_+ >> \omega_z >> \omega_-$$

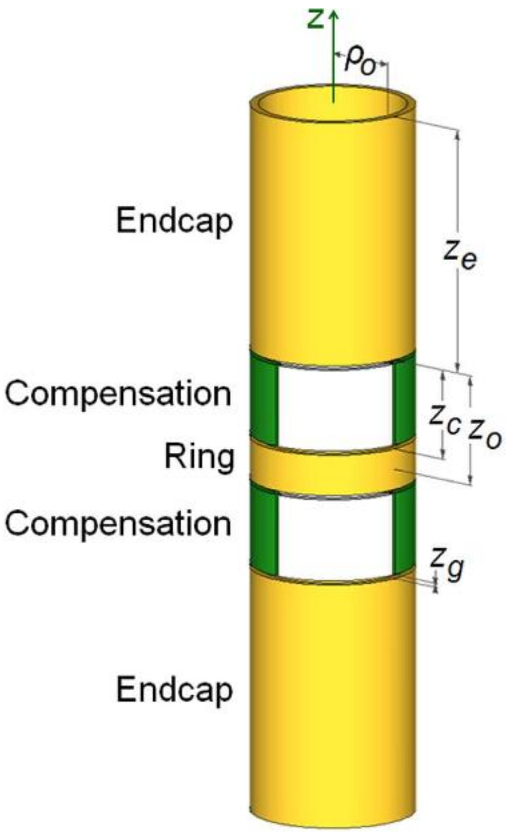
ω_+ detected in standard FT-ICR

$$\omega_c = \omega_+ + \omega_-$$

ω_c detected with quadrupole pickup FT-ICR

Minitrap Electrode Geometry

Cylindrical shaped, Open-endcap, Electrically compensated



Electrostatic potential only quadratic near trap center, more generally :

$$V = \frac{V_{DC}}{2} \sum_{n=0}^{\infty} C_n \left(\frac{r}{d}\right)^n P_n(\cos\theta)$$

n = odd coefficients C_n = 0, symmetry
n = 2, C_2 represents quadrupole potential
n = 4, 6, … anharmonic shifts to normal modes ω_z, $\omega_\pm$

$$\frac{\Delta\omega_+}{\omega_+} = \frac{3}{2}\left(\frac{\omega_-}{\omega_+}\right)^2 C_4 \left(\frac{\rho_+}{d}\right)^2$$, $\rho_+ \equiv$ orbital radius

$$\frac{\Delta\omega_+}{\omega_+} = -\frac{15}{8}\left(\frac{\omega_-}{\omega_+}\right)^2 C_6 \left(\frac{\rho_+}{d}\right)^4$$

Minimize anharmonicity through proper dimensioning of electrodes.

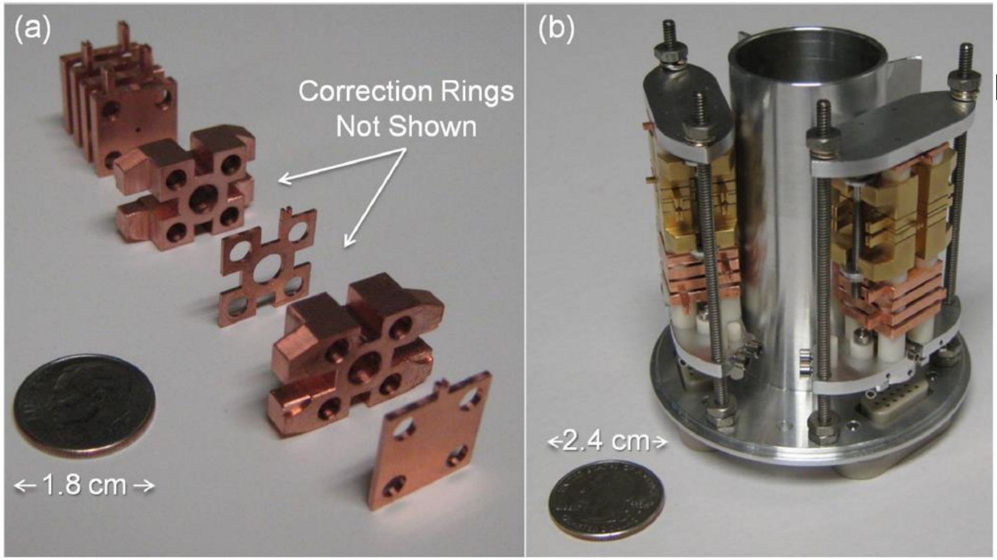
MSU Minitrap Dimensioning

Parameter	Value
ρ_0/z_0	0.990(13)
z_c/z_0	0.867(13)
z_e/z_0	2.970(14)
z_g/z_0	0.0495(40)
ρ_0	2.500(29) mm
z_0	2.525(29) mm
z_c	2.190(29) mm
z_e	7.500(26) mm
z_g	0.125(10) mm

Trap geometry “orthogonalized” via G. Gabreilse et. al. 1989

$\frac{\rho_o}{z_o}\left(\frac{z_c}{z_o}\right)$ enable tuning C_4 -> 0 via V_c without affecting ω_z & $\omega_\pm$

$\frac{z_c}{z_o} \approx 0.835$, simultaneous tuning C_4 & C_6 -> 0



→ Translume ↓ scale reduction and component integration in a fused silica platform

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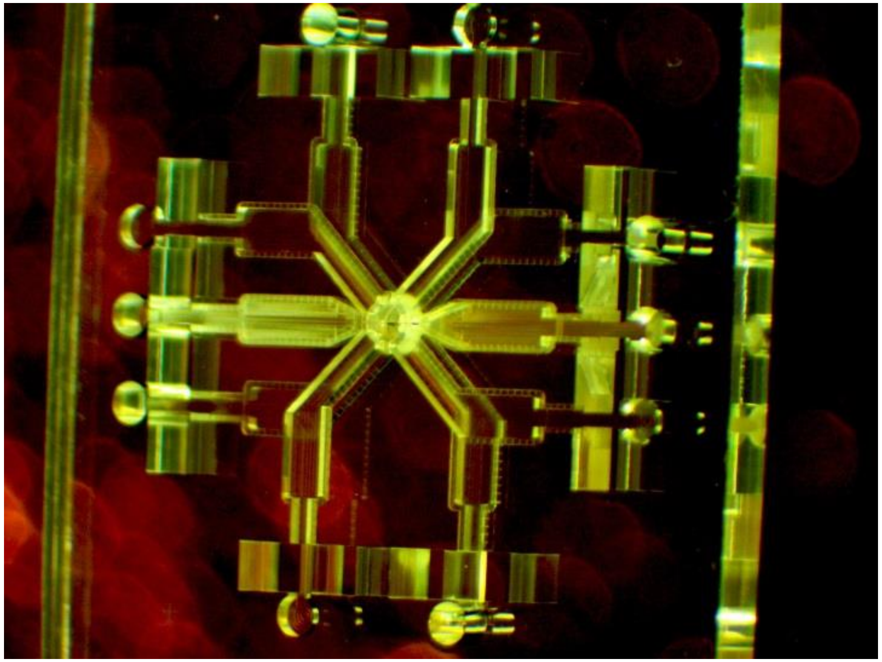
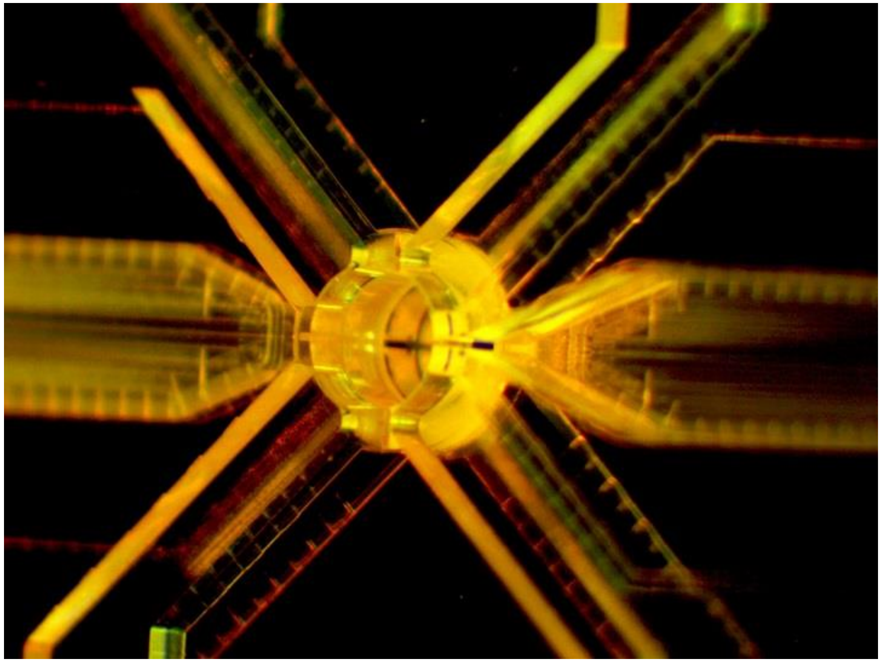
Ion Microtraps Fabricated Out of Fused Silica Glass : Step 1



Penning trap with 10 electrode access channels



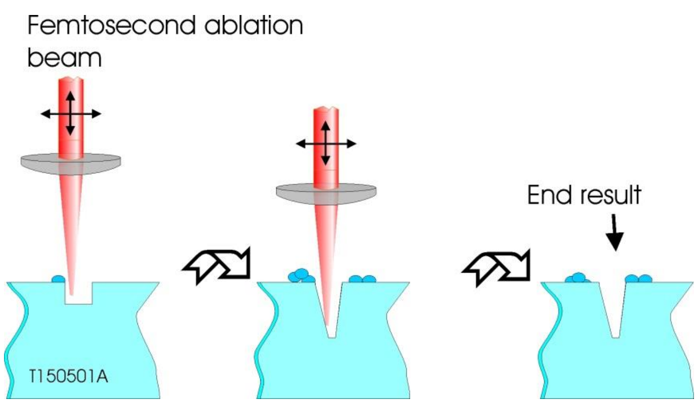
Penning trap central bore (1mm diameter)

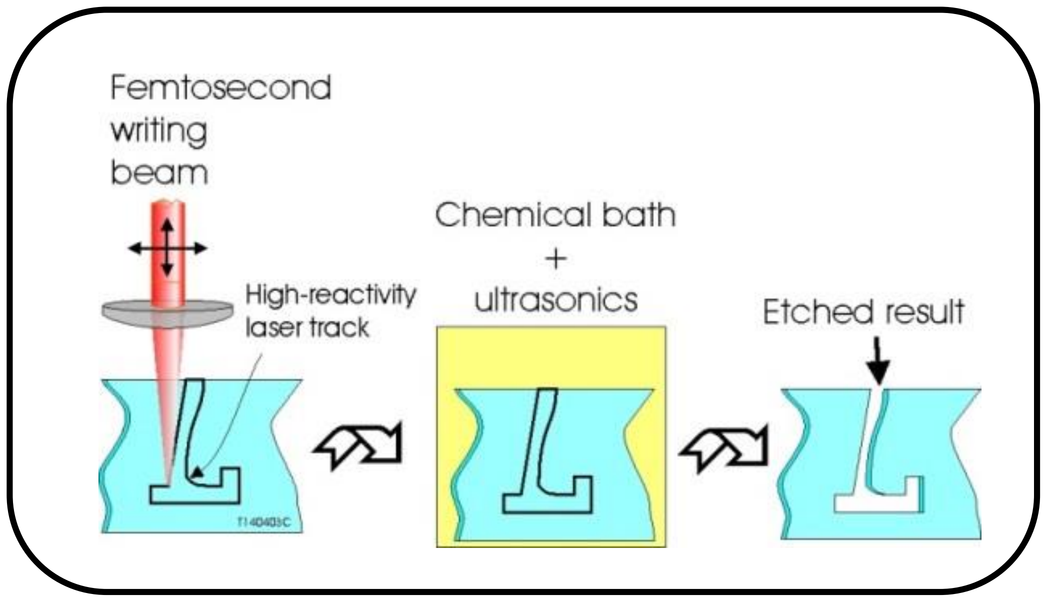
3D Laser patterning of the glass platform using *femtoEtch*™ process

Critical component formation and integration within a monolithic substrate

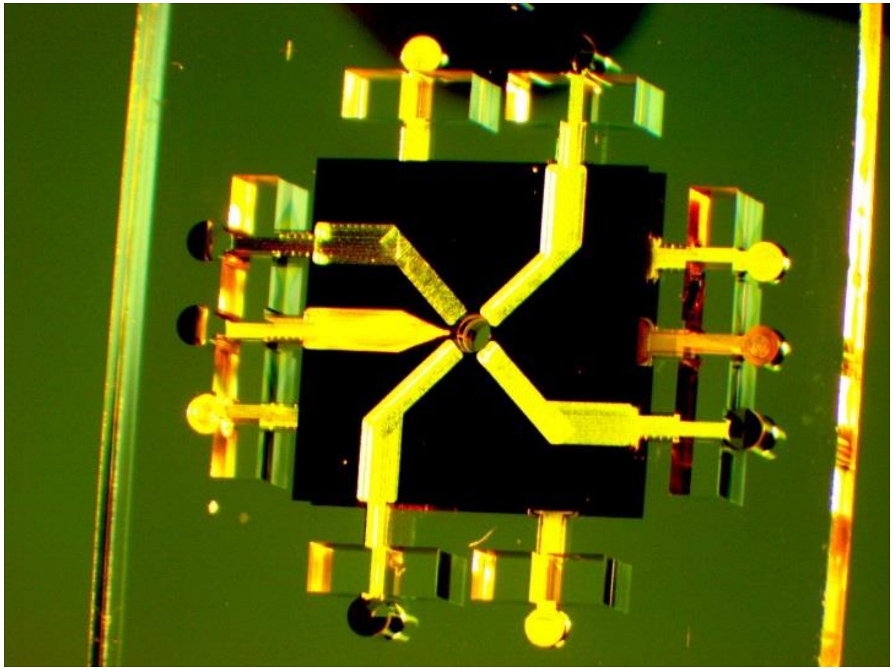
The *femtoEtch*™ Process

- NOT direct laser ablation of dielectrics
  - Debris generation, edge effects, *etc.*
- Combination of femtosecond laser direct-write and wet etching (*femtoEtch*) to shape fused silica
  - No ablation, no debris, no edge effects, true 3D geometry
  - Works best with fused silica glass

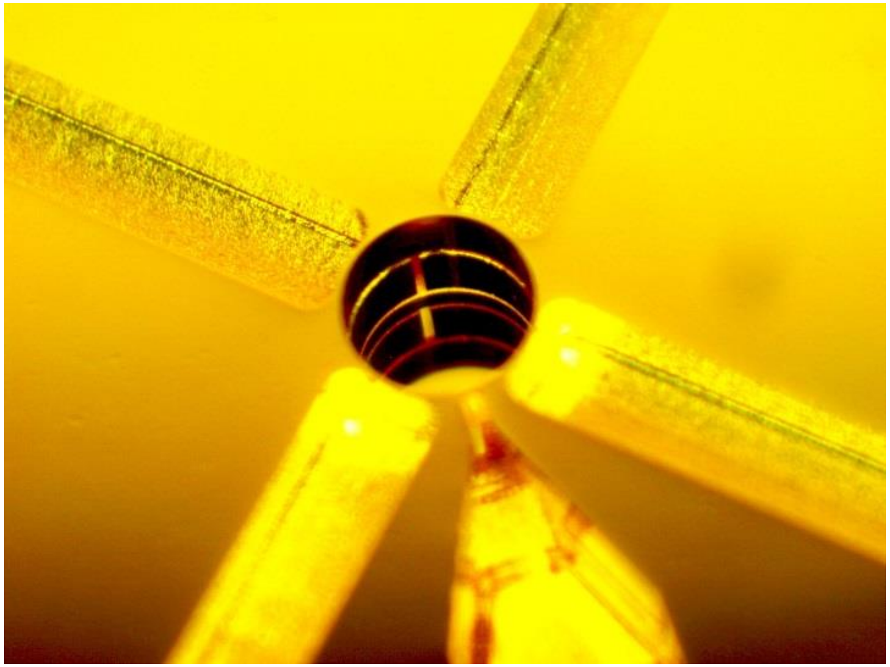




Ion Microtraps Fabricated Out of Fused Silica Glass : Step 2



Sputter coating: Au (1μ) on Ti (20nm)

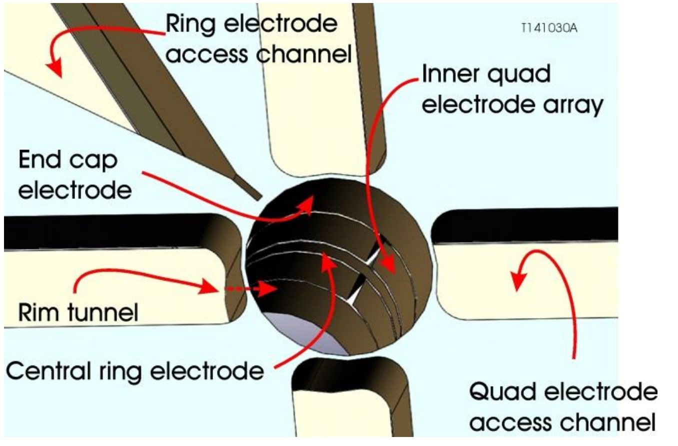


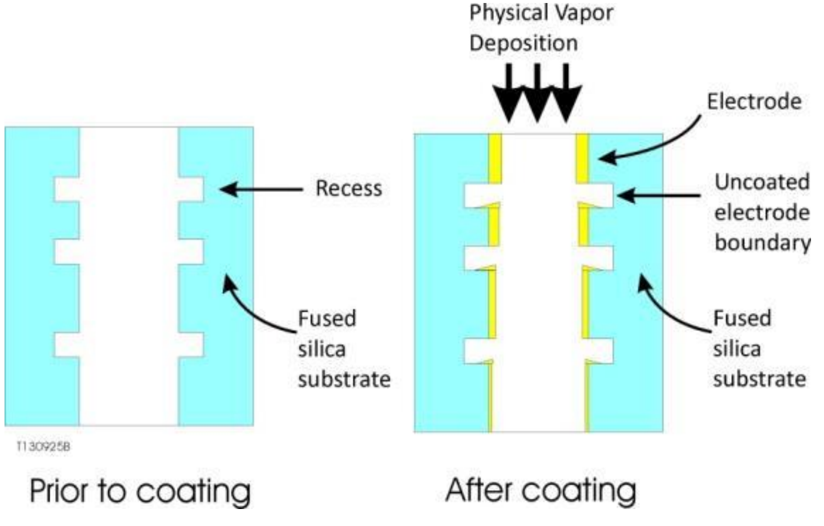
Coating from both sides for uniformity in center bore

Metal coating of the 3D platform forming 3D electrodes

Creating 3D Electrodes Using in-substrate High-aspect Features

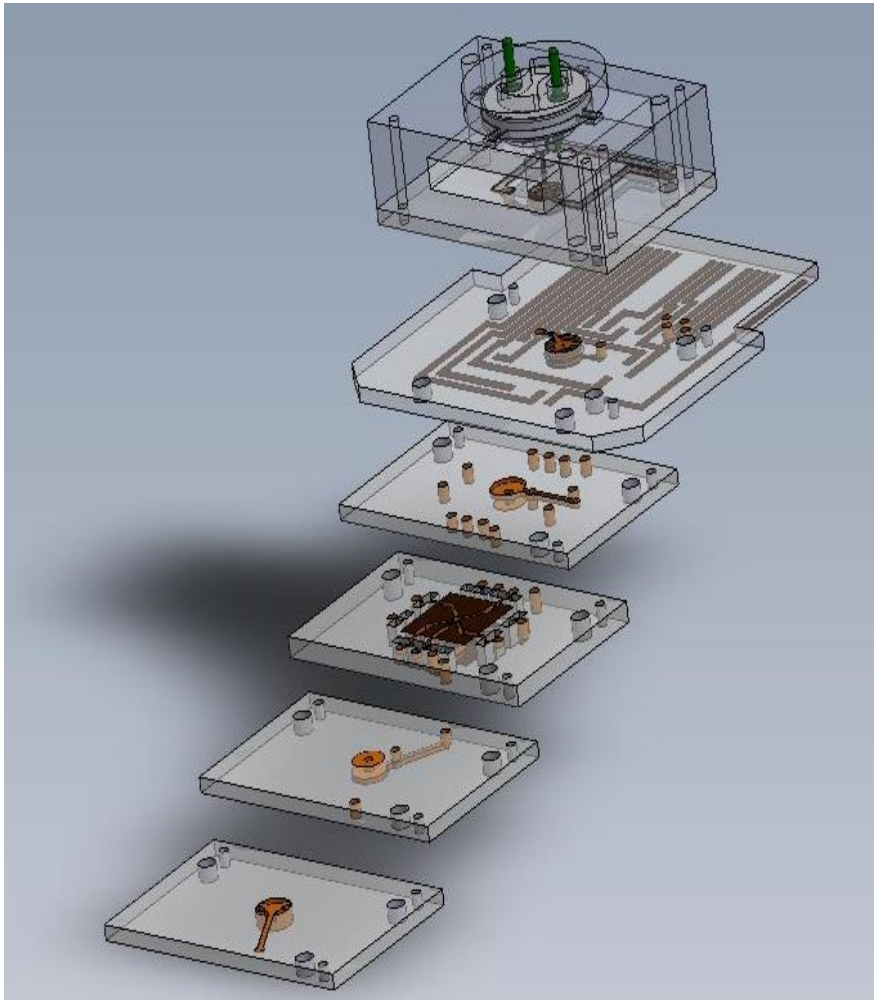
- Rely on the limited angular spread inherent in sputter coating to metalize contoured surfaces, including the side walls of recesses and high aspect features
- In some cases a secondary electro–plating process to increase coating thickness or extend coverage through tunnels
- Dielectric far from electrode interface





Penning Trap Magnetometer Assembly

- For now ionization achieved with commercial thermal e^{-} emitter (LaB_6)
- Trap electrode components fabricated monolithically within substrate
- Adjacent substrates aligned via precision hole & pin assemblies ($\pm 10\mu$)
- Electrical connection between substrates using "fuzz buttons"
- Electrode leads assembled on one surface for card connection and wiring
- All materials non-magnetic (Au on Ti coating, stainless steel, Au on BeCu)



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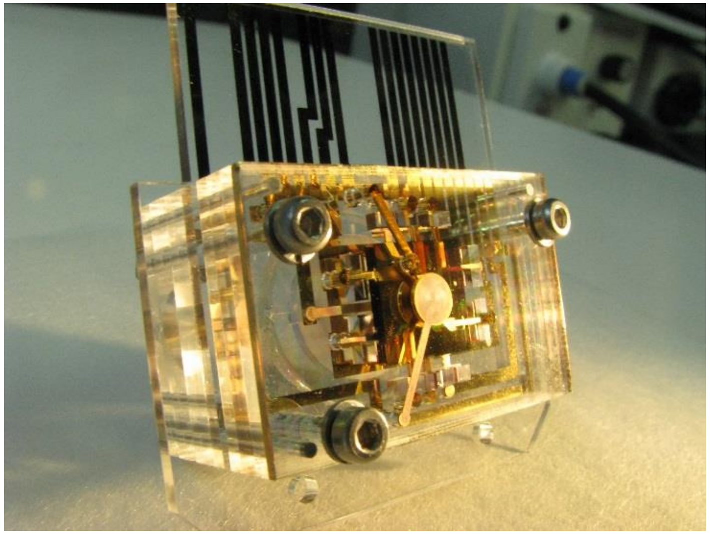
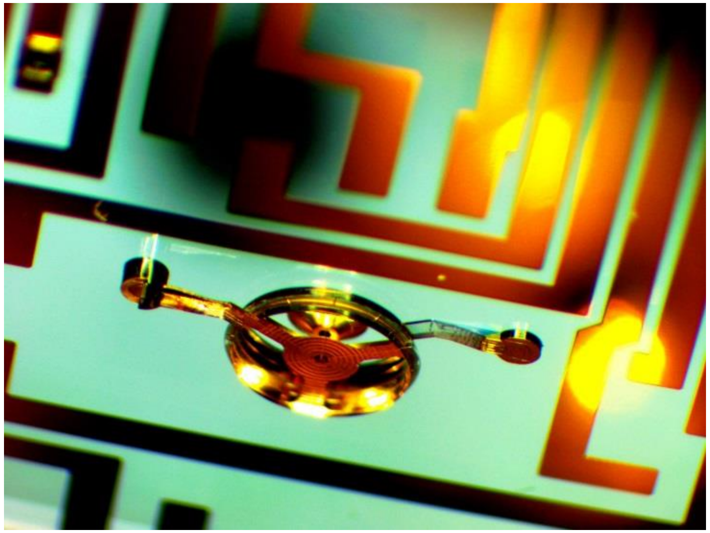
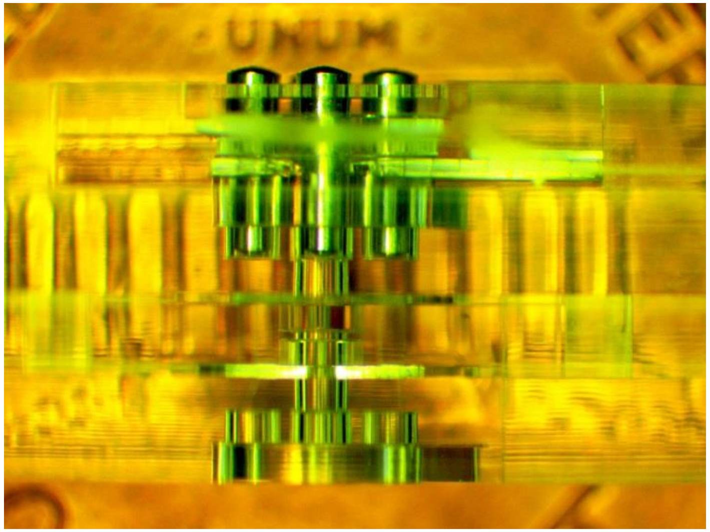
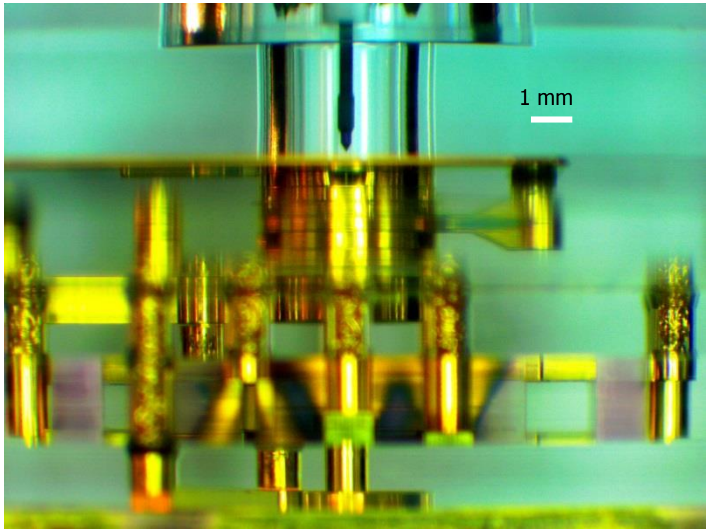
Penning Trap Magnetometer Assembly









Continuing & Future Work

- 1st generation device (5X reduced scale) is currently being tested in a 1.8T superconducting magnet at MSU
- 2nd device delivered with frame modifications for improved evacuation of trap bore and easier interconnect access
- 3rd device is currently being fabricated that is a 2.5X reduced scale of the original MSU minitrap
  - Compare with 1st generation device performance
- Reducing overall device size
  - Improve ionization source.
  - Redesign connector and cable assembly
- Sealed high vacuum probe

Contact Info

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