Batch Fabrication of Radial Anisotropy Toroidal Inductors

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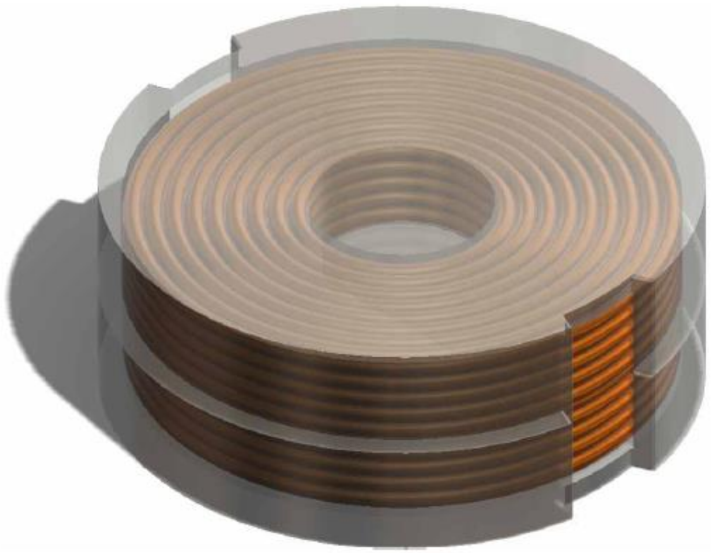
THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

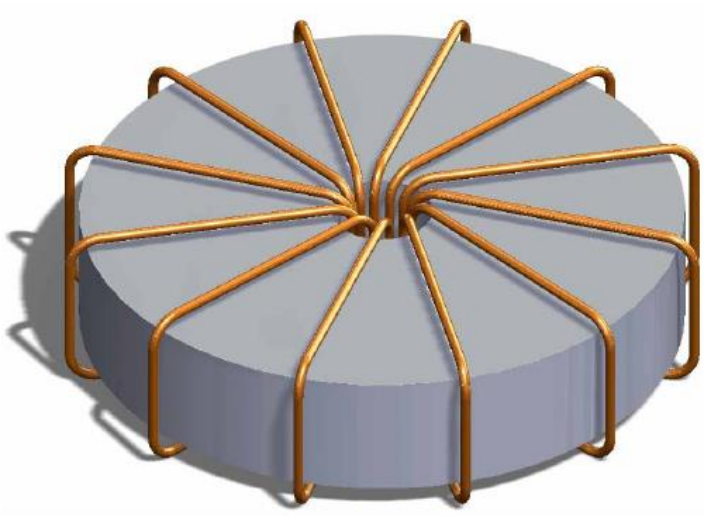
Two types of inductors

Pot-core



- Core wraps winding

Toroidal

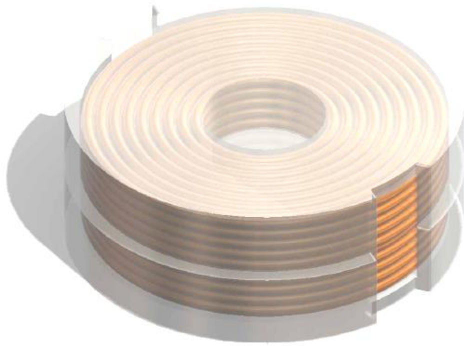


- Winding wraps core

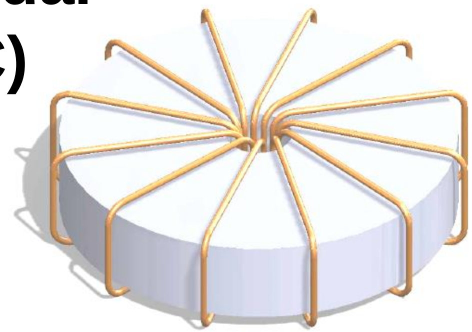
- Many intermediate geometries are also possible

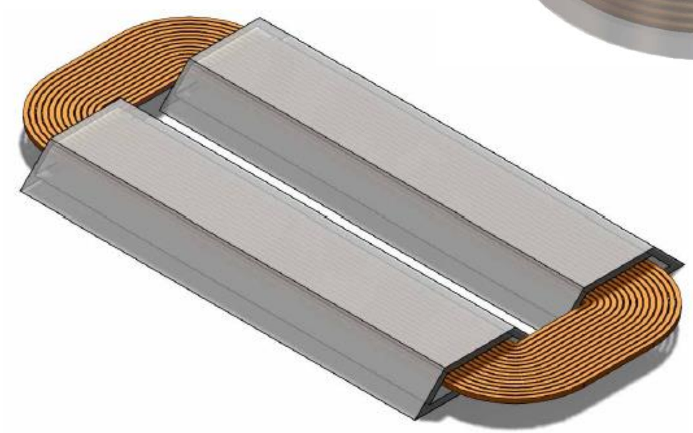
Inductors on Si

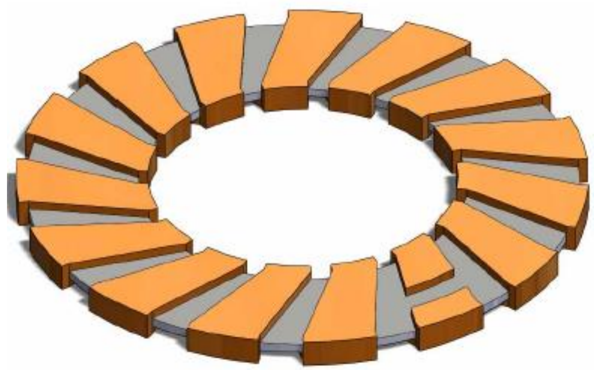
Pot-core (MCM)

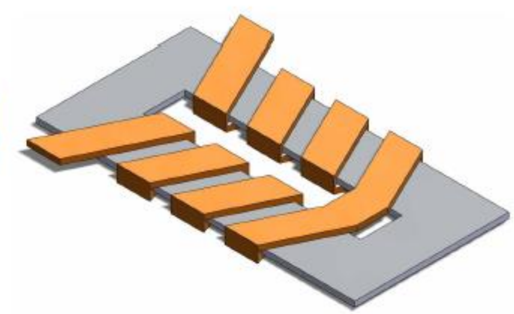


Toroidal (CMC)





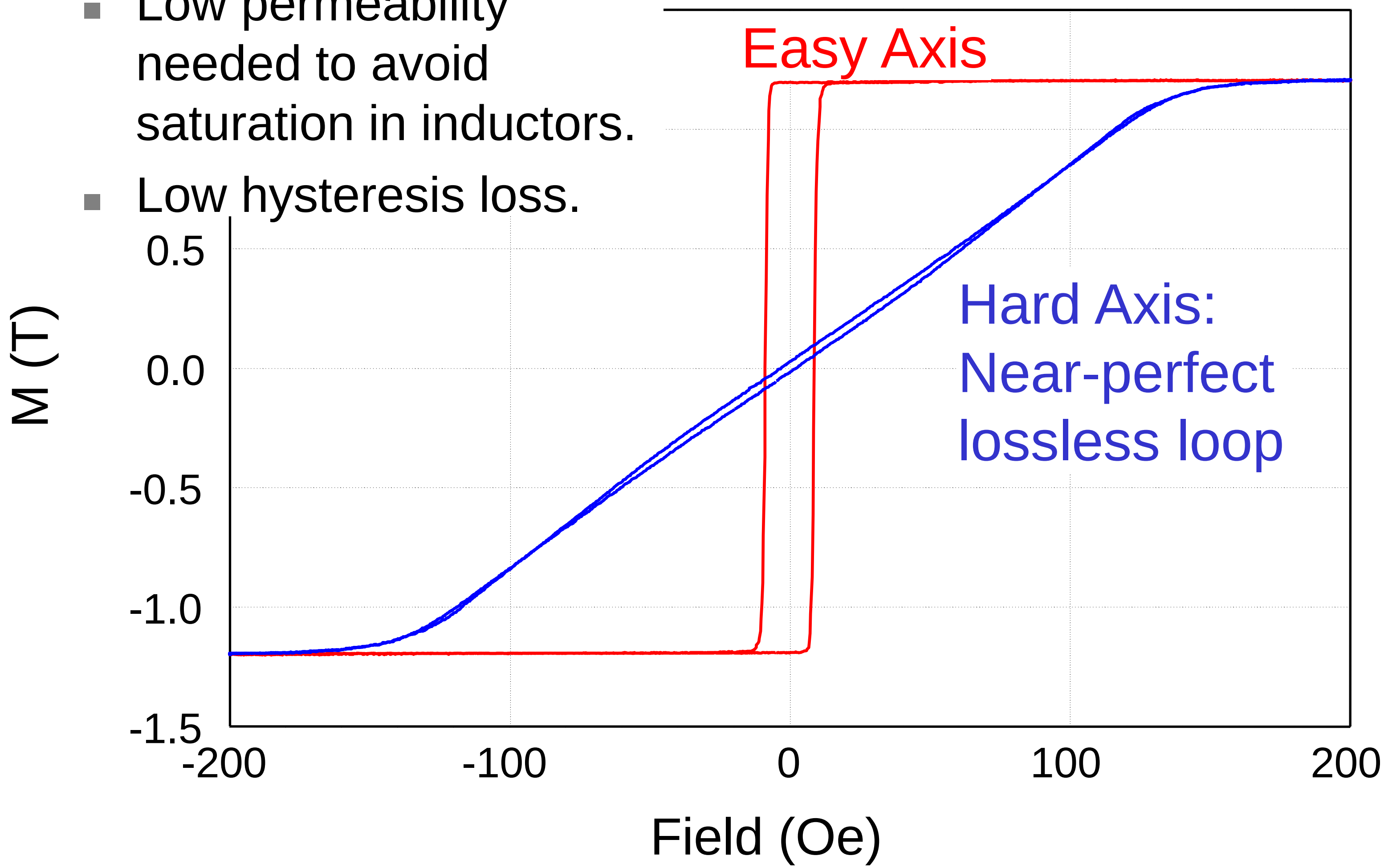




- Two magnetic depositions
- One magnetic deposition.

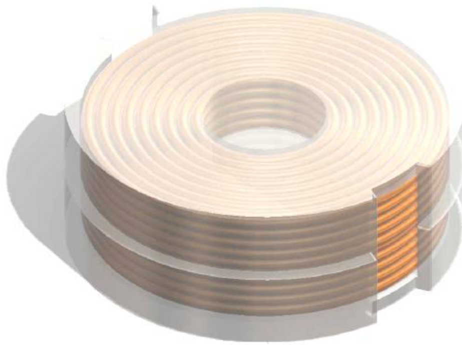
Magnetic anisotropy: common in thin-film magnetic materials

- Hard axis loop provides:
  - Low permeability needed to avoid saturation in inductors.
  - Low hysteresis loss.

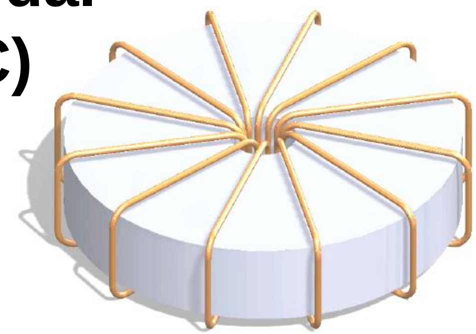


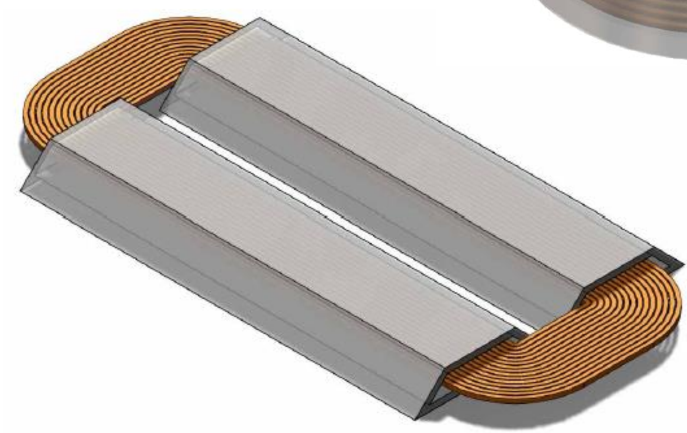
Microfabricated inductors

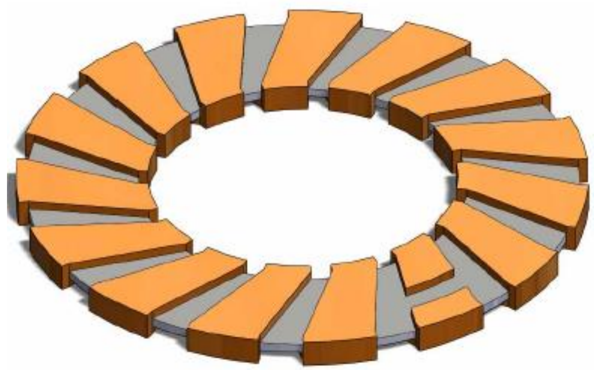
Pot-core (MCM)

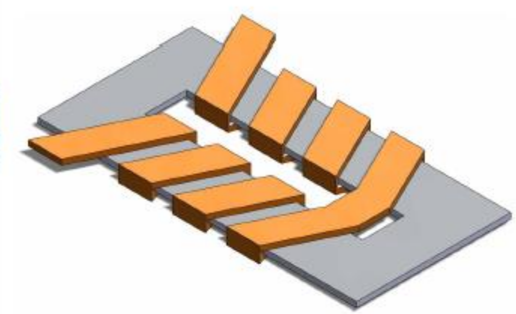


Toroidal (CMC)



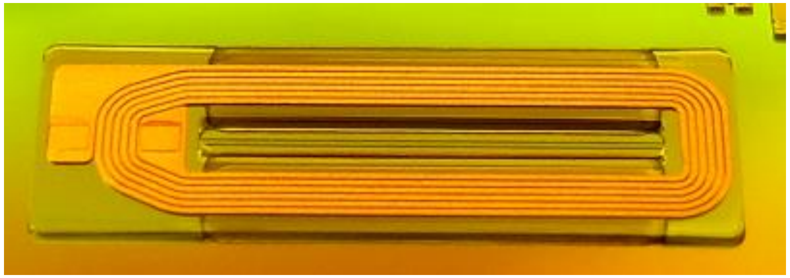


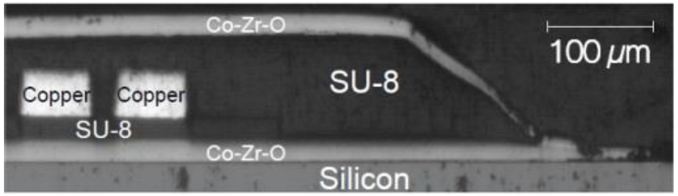


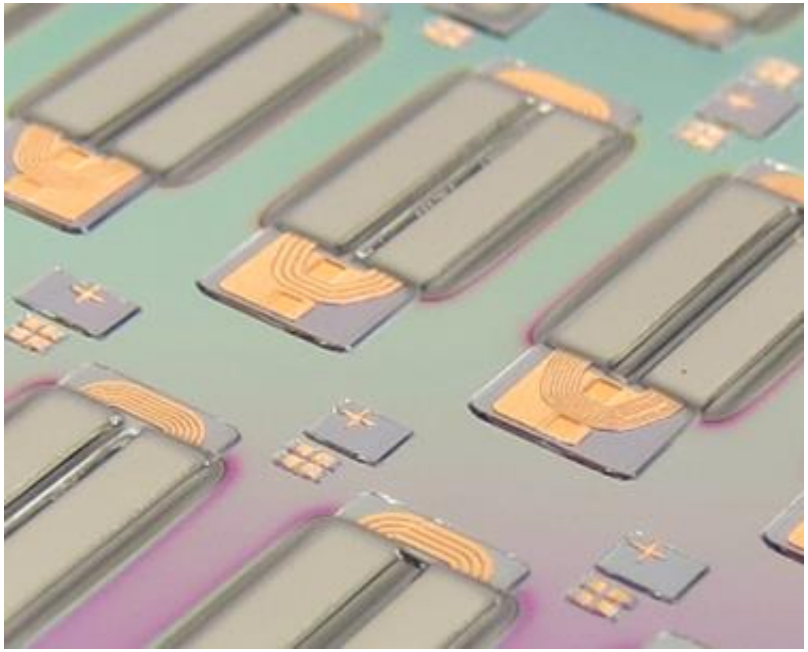


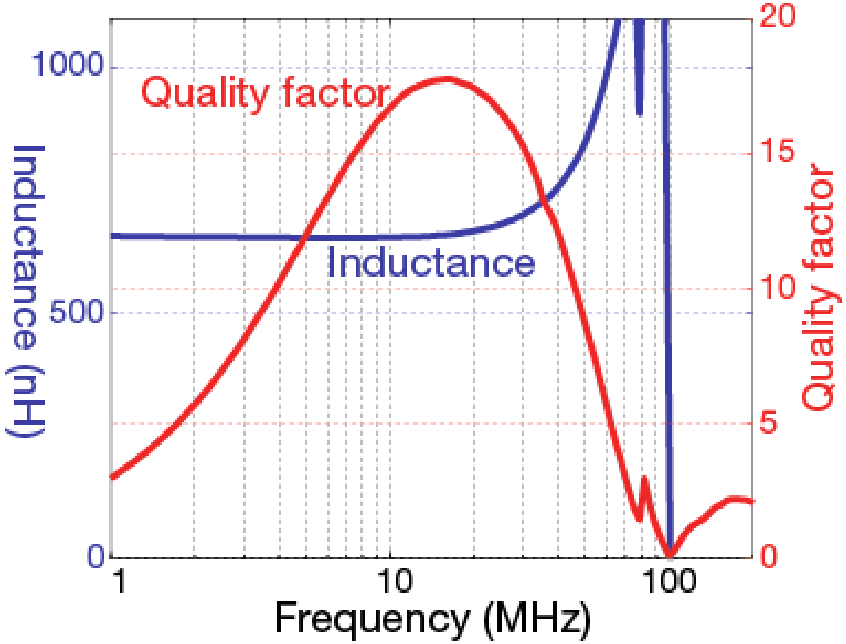
- Two magnetic depositions
- **Uses magnetic material only in hard axis**
- **Does not work with uniaxial anisotropy**

Racetrack inductors fabricated at Dartmouth



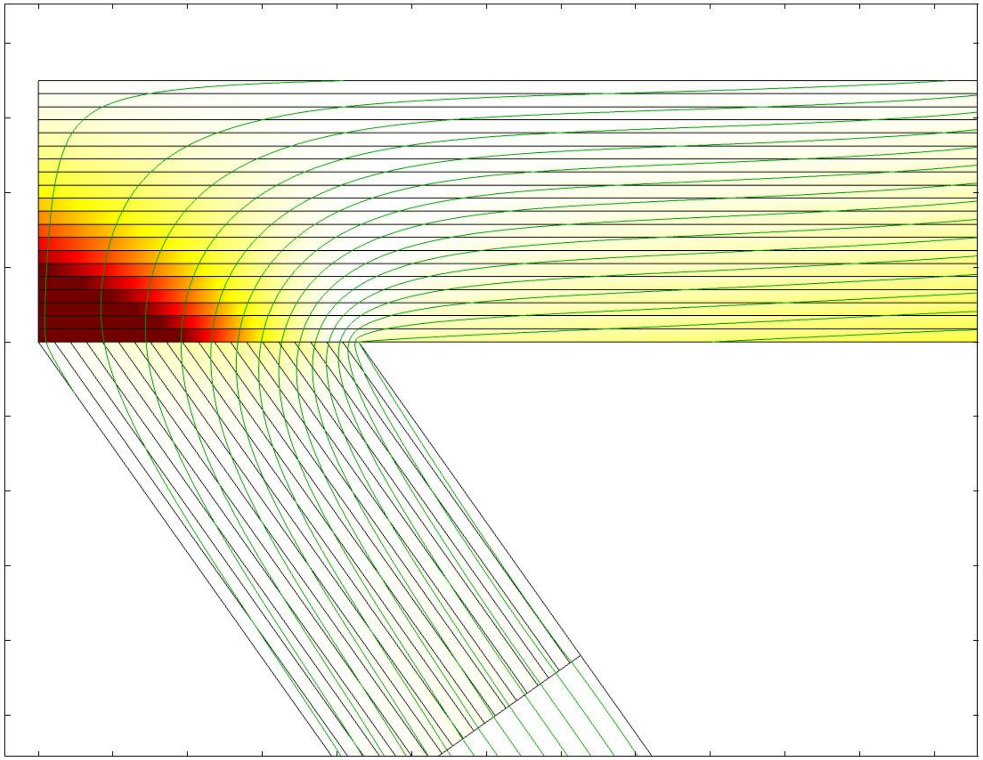




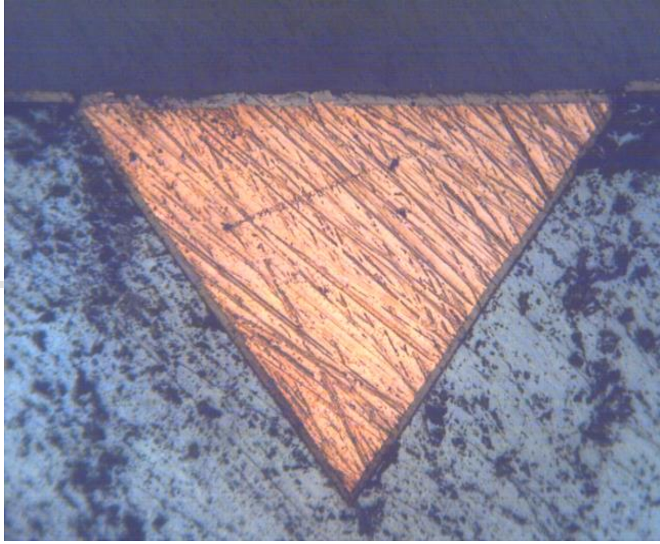


Flux crossing magnetic laminations

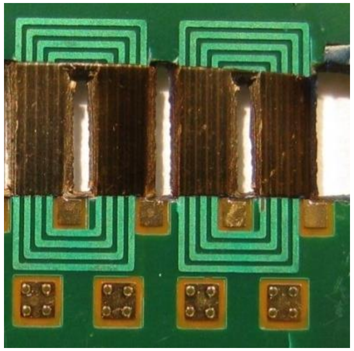
- Problem in corners where top and bottom magnetic core halves join.
- Excess eddy currents limit efficiency and Q.
- Power loss, due to **o**ut-**o**f-**p**lane **f**lux (OOPF): P_{OOPF}.



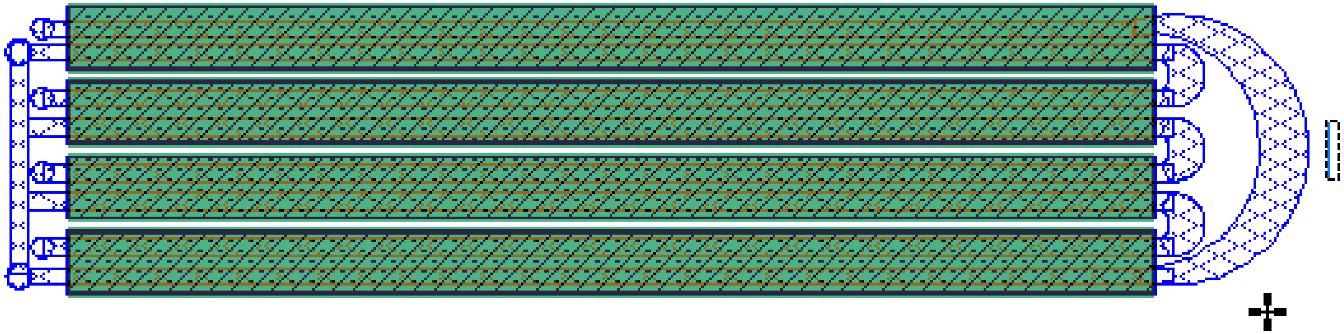
Variations on the theme: Other designs with the same problem.

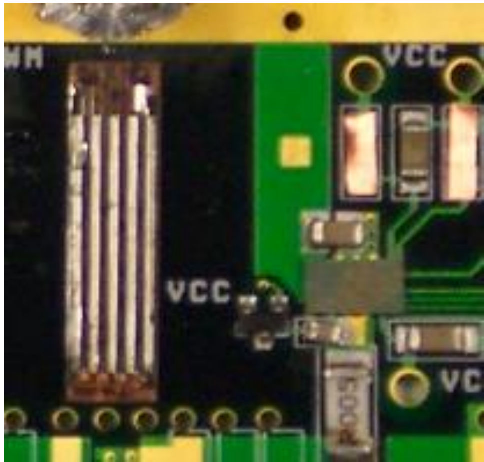


- V-groove 1-turn inductor for high current (up to 12 A)
- Polyimide substrate with sputtered material on both sides

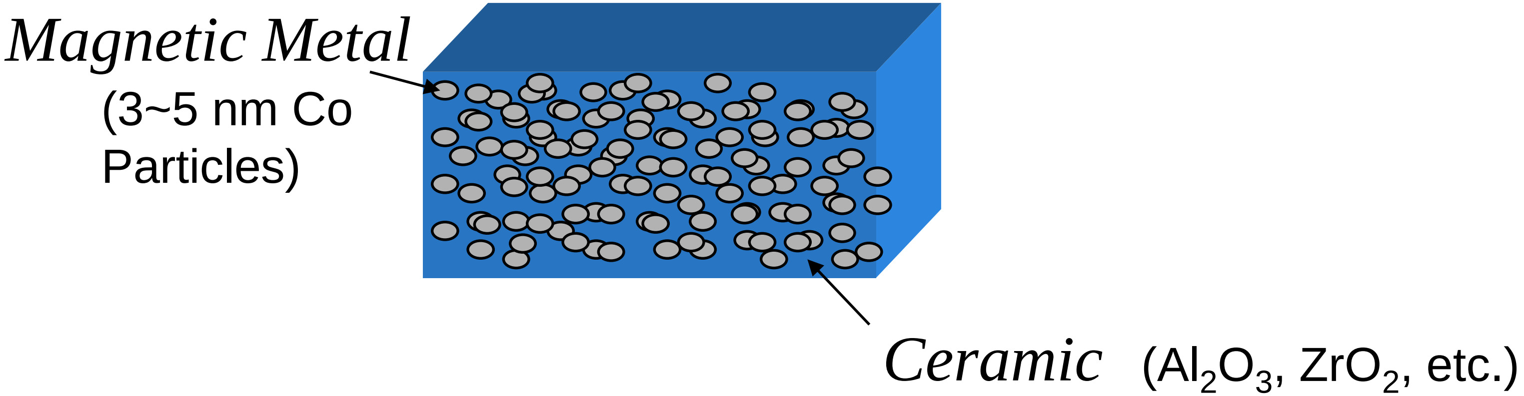


- Microfabricated coupled inductors (2004, with Tyndall)





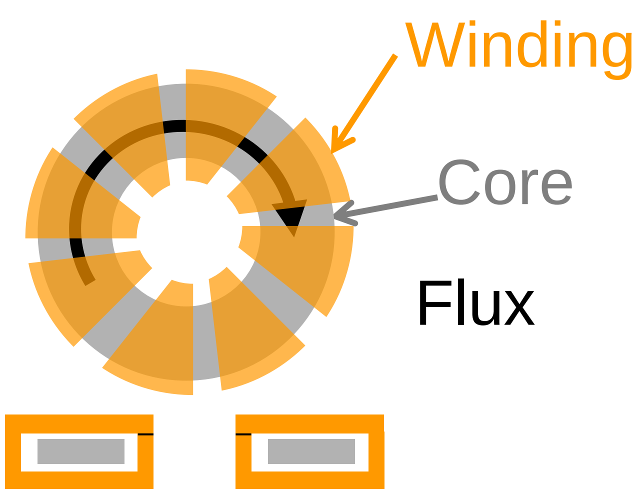
Nano-composite magnetic materials



- Ferromagnetic (coupled particles)
- Some have strong anisotropy for low permeability and low hysteresis loss.
- High resistivity (300 ~ 600 μΩ·cm) reduces eddy-current loss for any flux direction.
- Eddy currents due to out-of-plane flux still dominate loss. P_{OOPF} is still a problem.

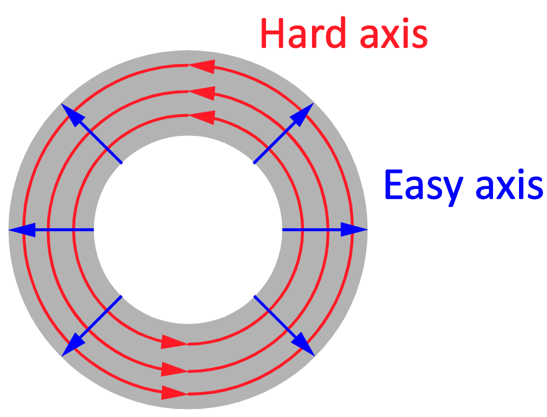
Toroidal Inductors: No out-of-plane flux! No P_{OOPF}!

- **Advantage:**
  - Flux stays in plane, minimizing eddy-current losses.
- **Challenge:**
  - Flux direction varies; sometimes oriented incorrectly for the magnetic material anisotropy.
- **Solution:**
  - Induced radial anisotropy, such that flux travel is always in the low-loss hard-axis direction.

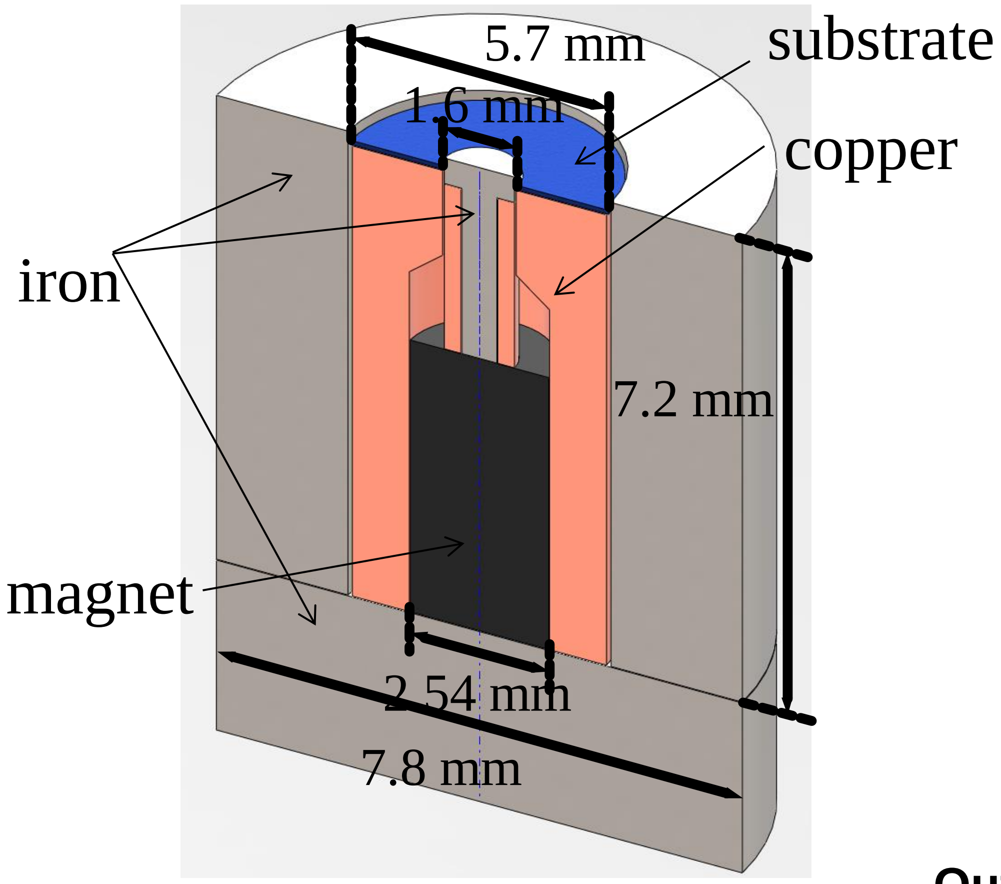


Radial anisotropy

Qiu and Sullivan. APEC, 2012

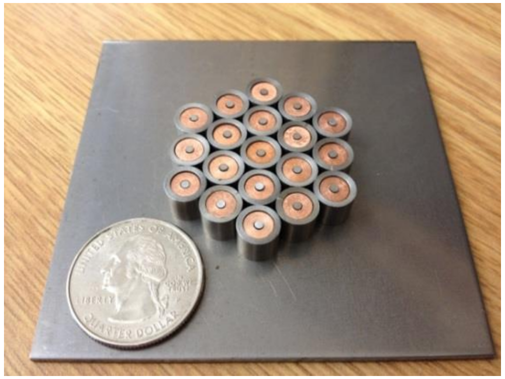


Fixture to deposit toroidal cores with radial anisotropy

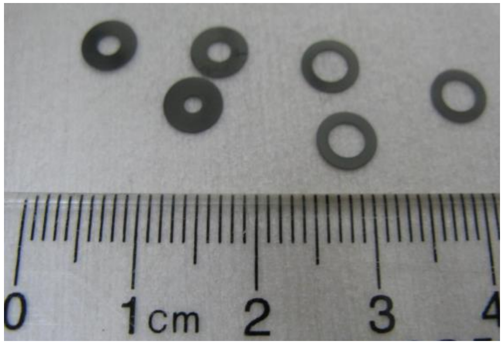


Qiu and Sullivan , CIPS, 2012

Fabricated array of fixtures



Co-Zr-O radial-anisotropy cores



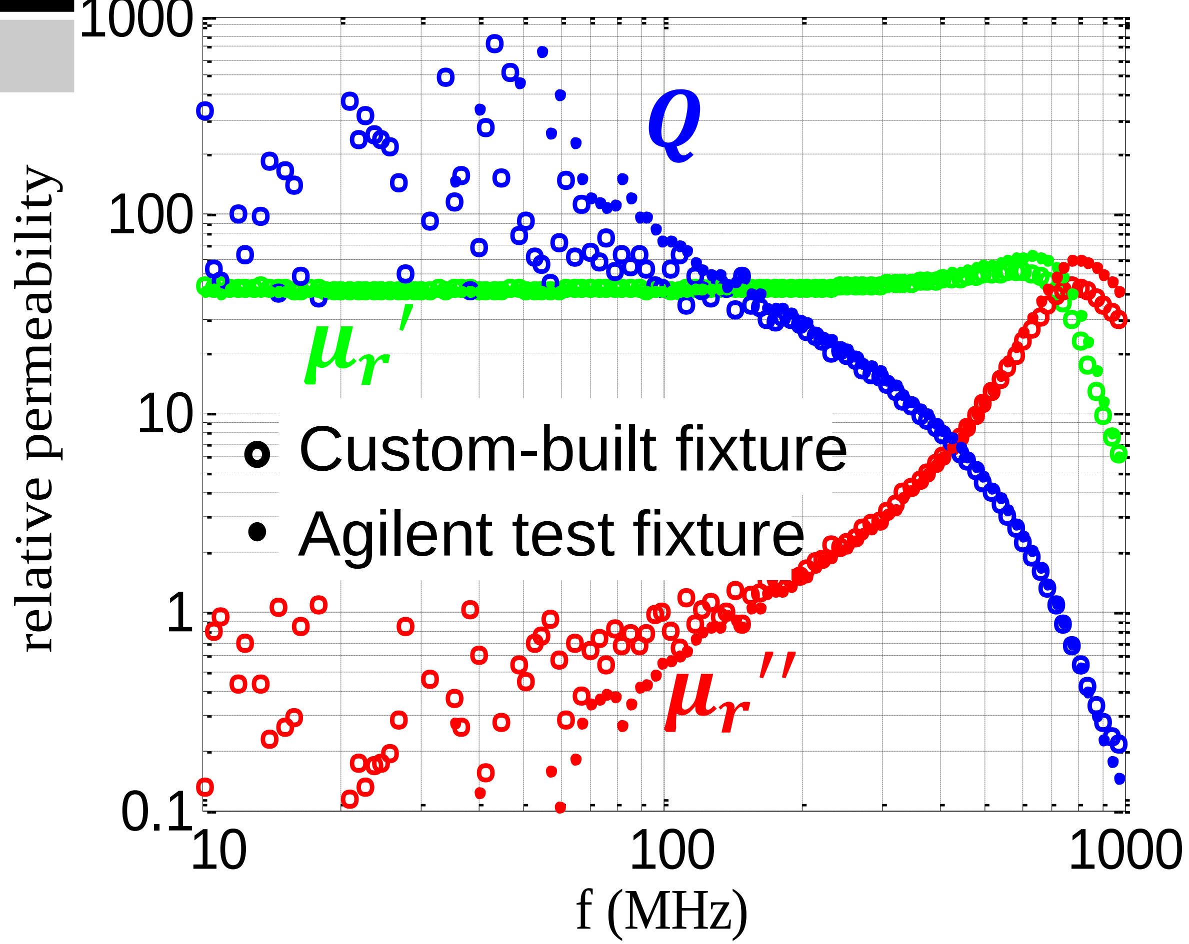
Outer diameters: 5.5 mm
Inner diameters: 1.7 mm, 2.3 mm, 3.4 mm
Thickness: 6 μm, 40 μm

Permeability of radial-anisotropy cores

Outer diameter	Inner diameter	thickness
5.5 mm	3.4 mm	40 μm

- High Q: ~ 100 at about 60 MHz.
- Resonance at about 800 MHz.
- Two test fixtures agree.

Measured by both fixtures

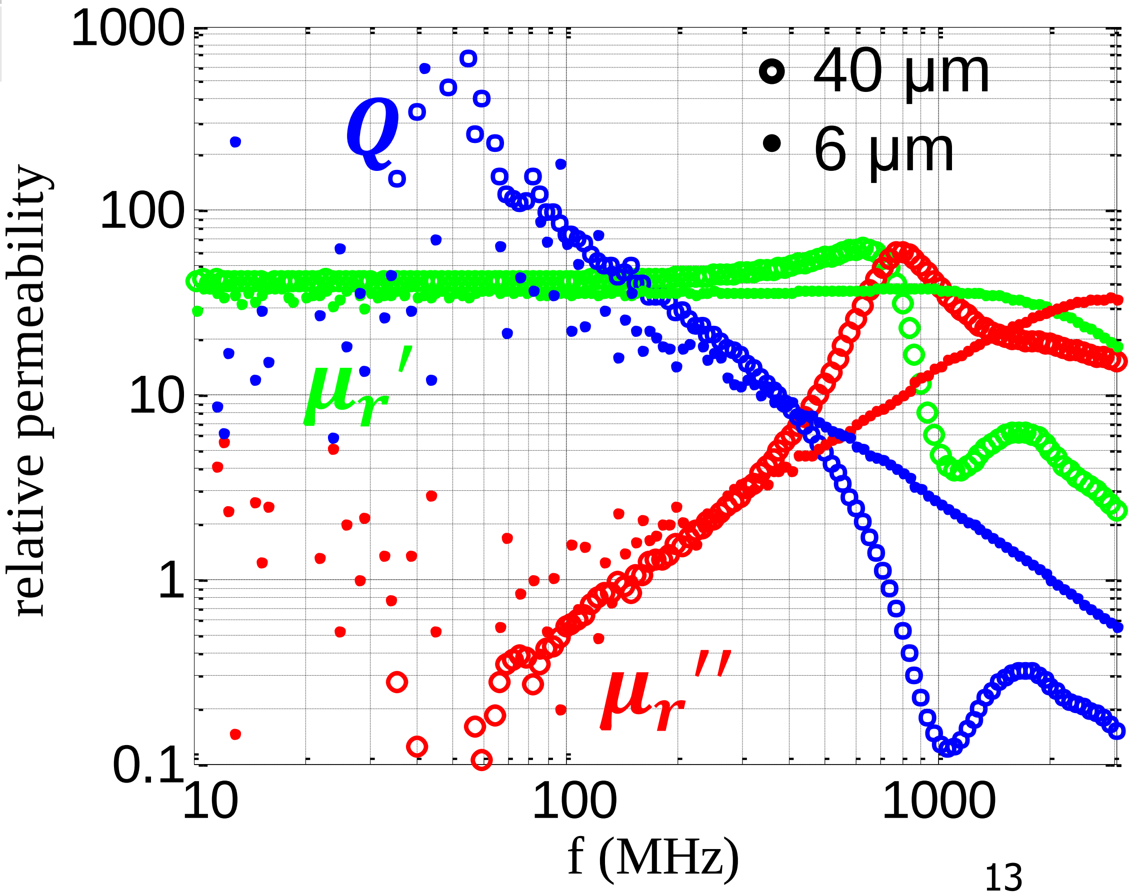


Permeability of radial-anisotropy cores with different thicknesses

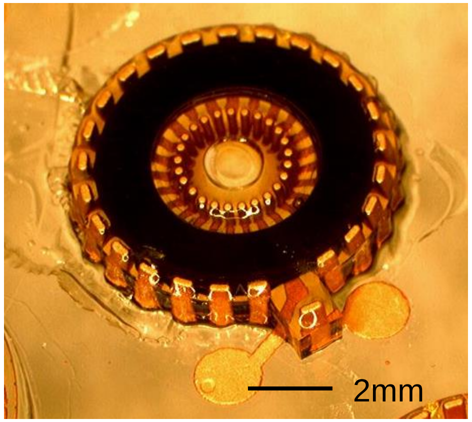
Outer diameter	Inner diameter	thickness
5.5 mm	3.4 mm	40 μm
5.5 mm	3.4 mm	6 μm

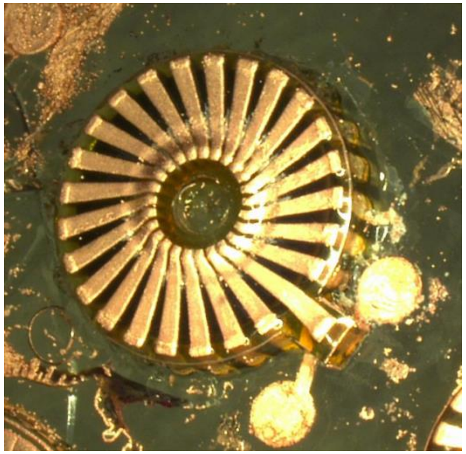
- Both cores show a real part of relative permeability of about 40.
- Both cores show Q~100 at f < 100 MHz.
- Characteristics differ at f > 500 MHz:
  - The thicker core has a lower resonant frequency, presumably a self-resonance of the multi-layer structure.

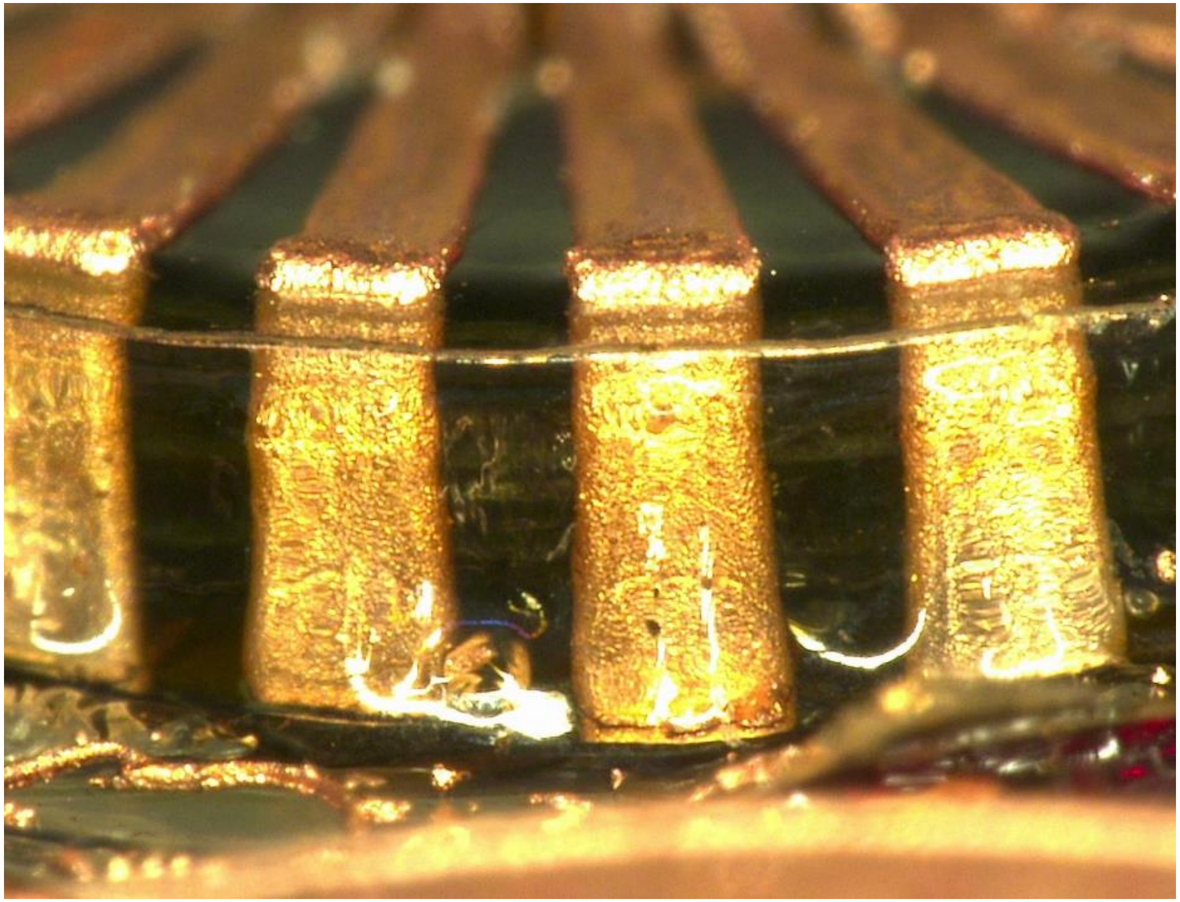
Measured by Agilent test fixture



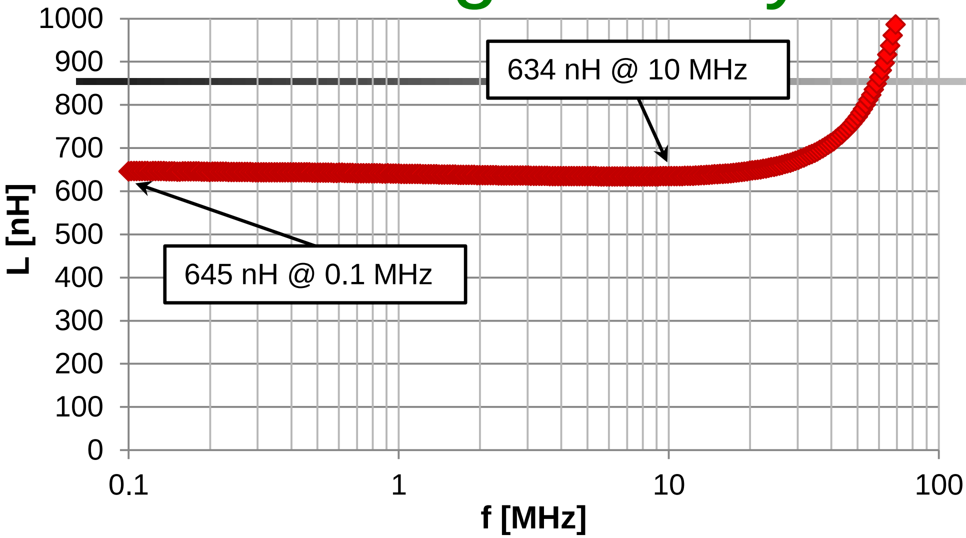
CoZrO core integrated inductor: Dartmouth cores integrated by Georgia Tech

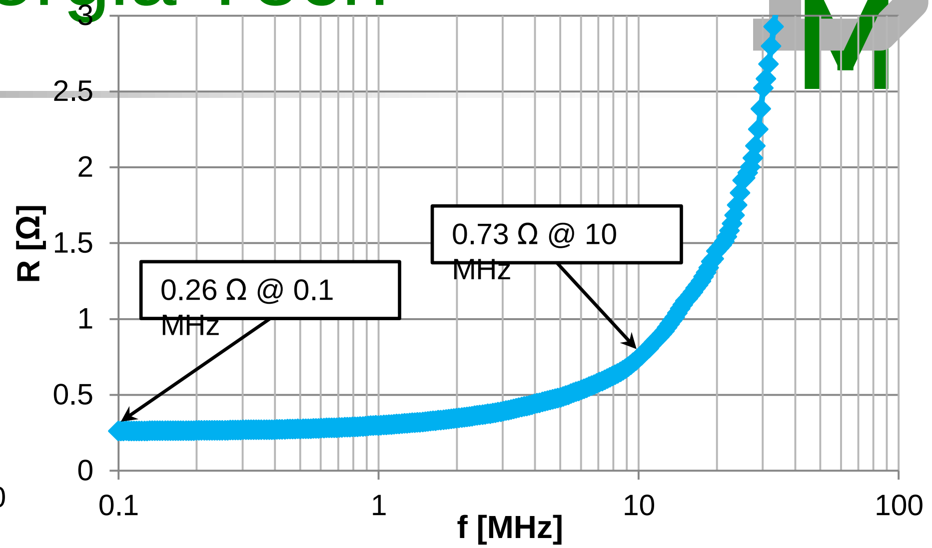


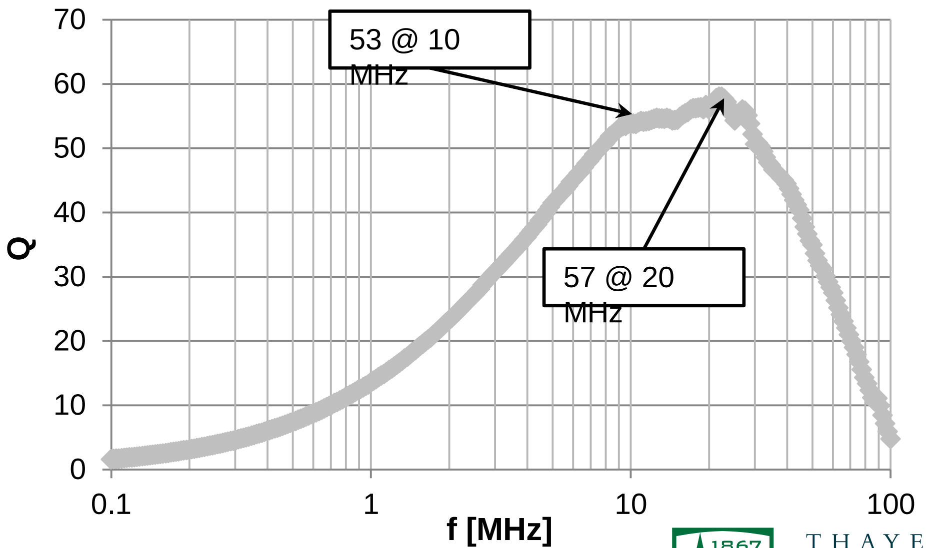


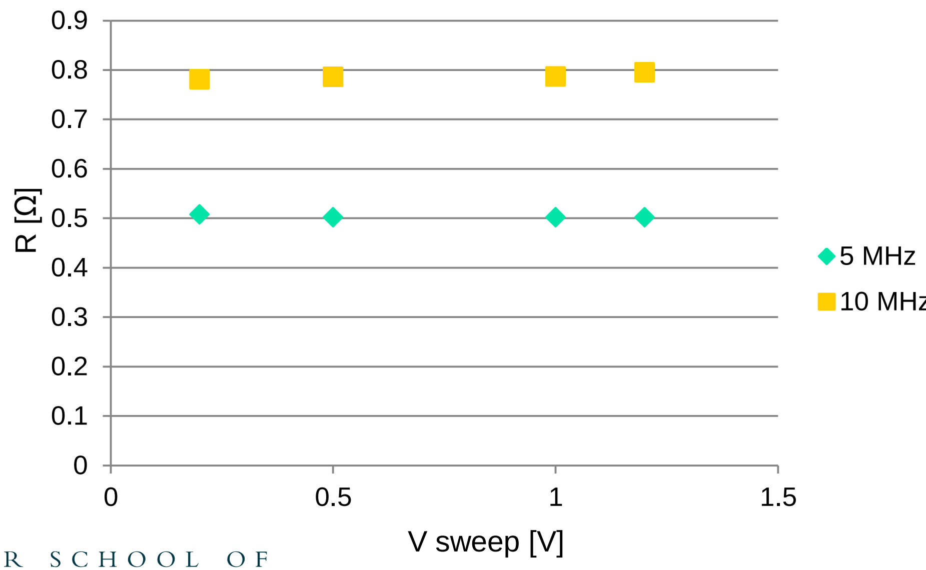


CoZrO core integrated inductor: Dartmouth cores integrated by Georgia Tech









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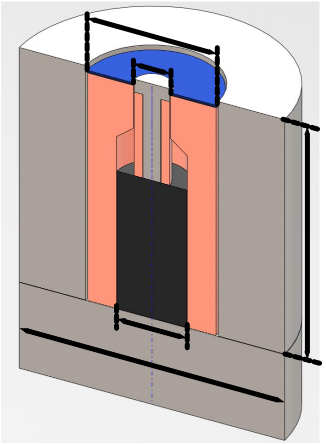
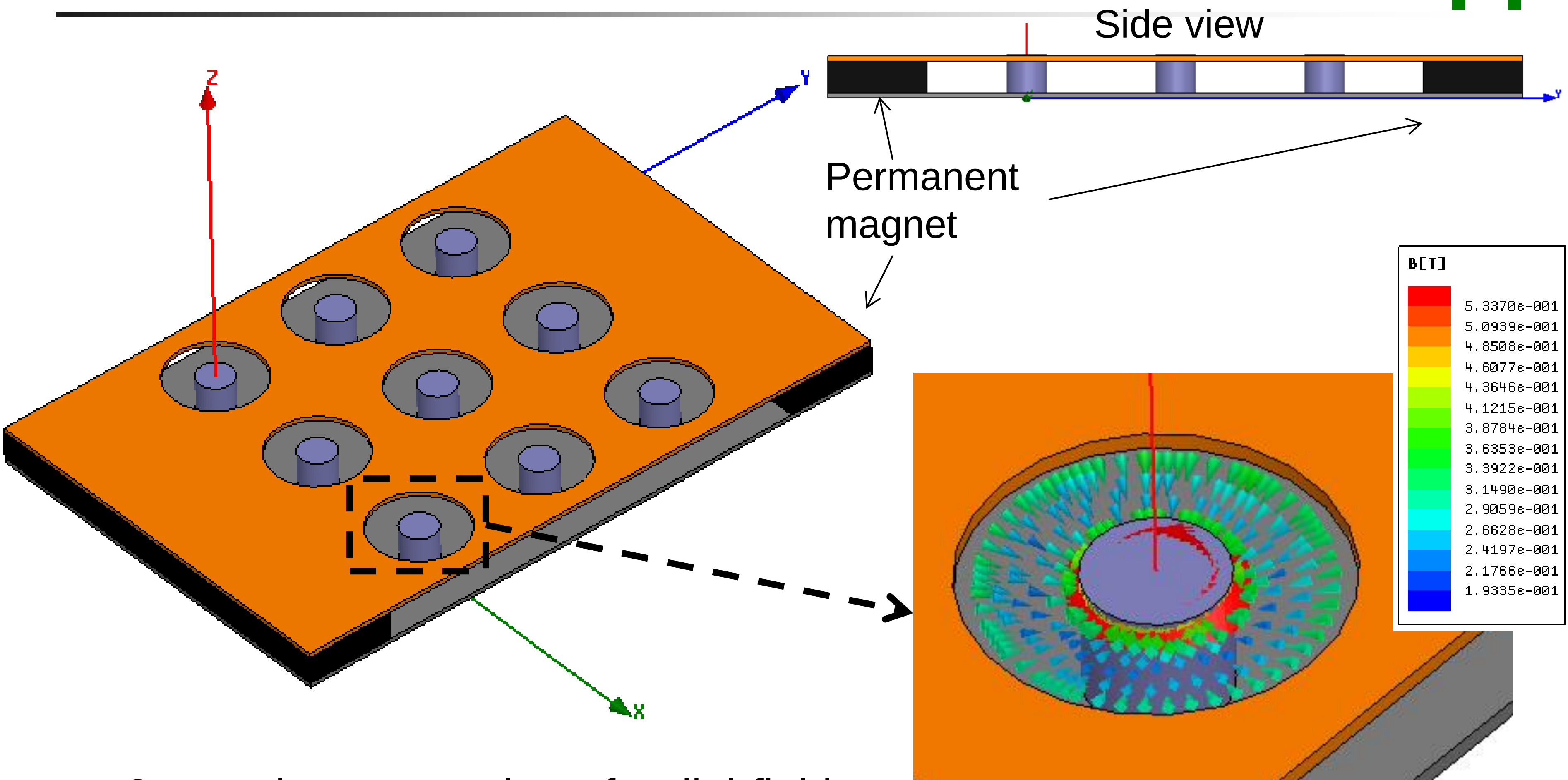
Batch fabrication

- Cores were deposited on individual substrates, and manually dropped in windings at process mid-point.
- OK for a demonstration project, but can we do true batch fabrication?
  - Many on one substrate.
  - All processes on one substrate.
  - Avoid the need for a tiny magnet for each.

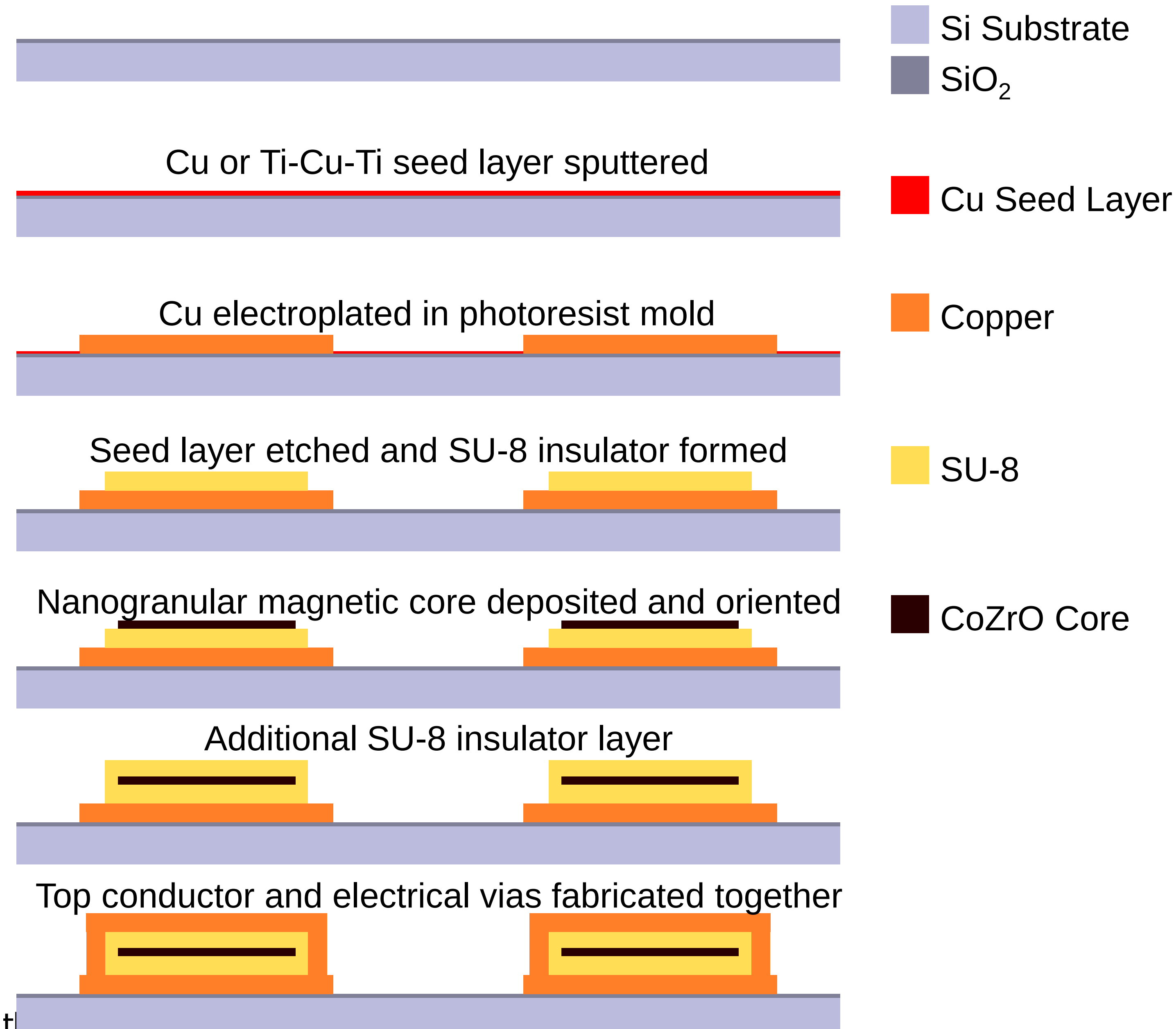


Shared-magnet radial-field fixture

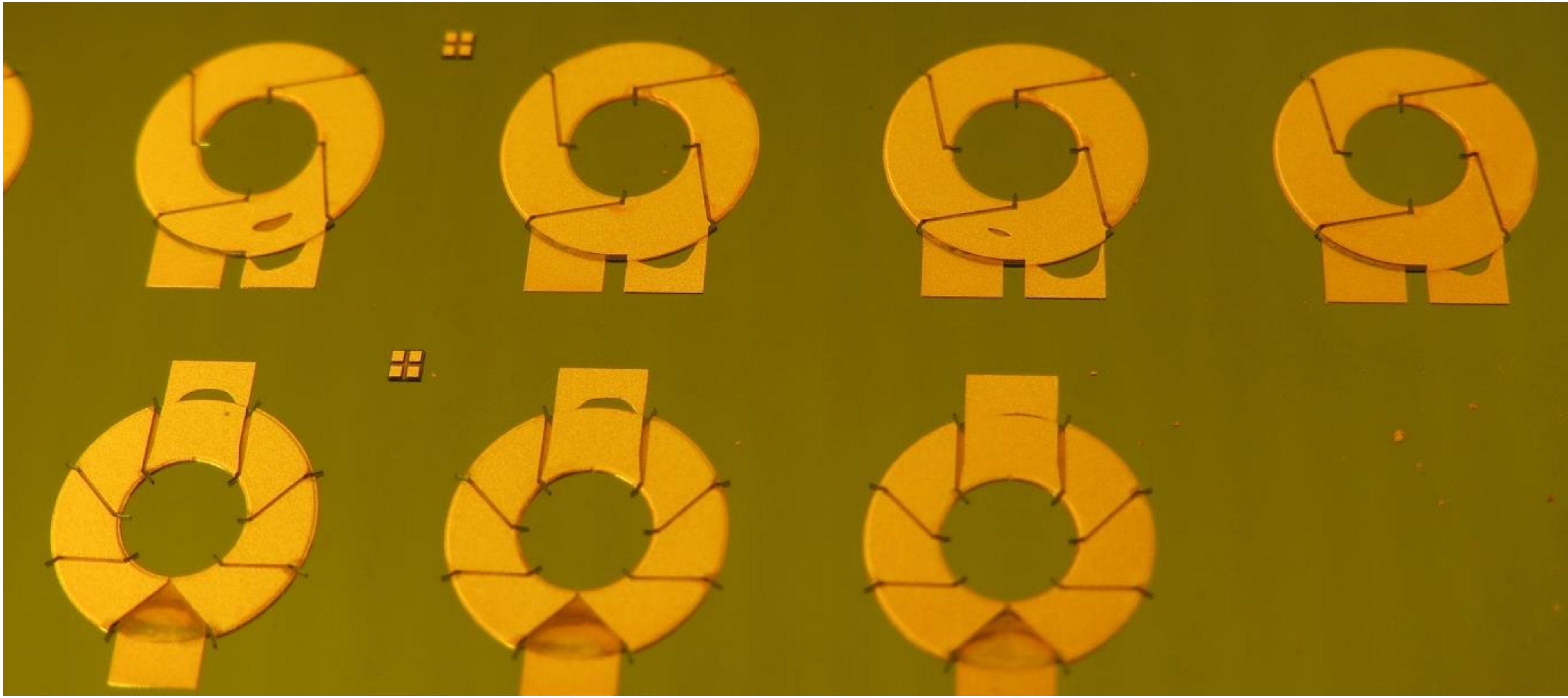


- Can make any number of radial-field regions with only two magnets.
- Can photo etch new top plate for a new design.

Process flow



Samples with dummy core



All four-turn inductors—lower winding design minimizes capacitance.

See Jizheng Qiu, A.J. Hanson, C.R. Sullivan, "Design of toroidal inductors with multiple parallel foil windings“ Control and Modeling for Power Electronics COMPEL 2013.

Summary

- Effective utilization of laminated anisotropic materials:
  - Toroidal designs keep the flux in the plane so laminations effectively squelch eddy currents.
  - Radial anisotropy keeps hysteresis losses low.
- Radial anisotropy can be induced by applying a field during deposition.
  - Fixtures for discrete cores.
  - Shared-magnet fixture: any number feasible on a single substrate. (100?)

Thank you

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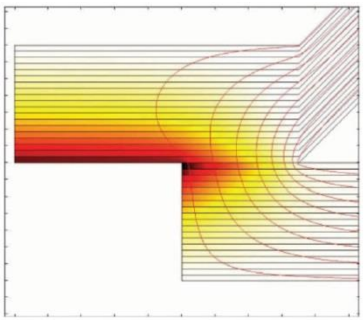
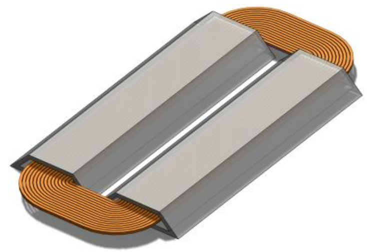
Thin-film inductor geometries

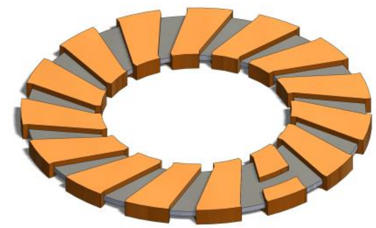
Via loss in racetrack



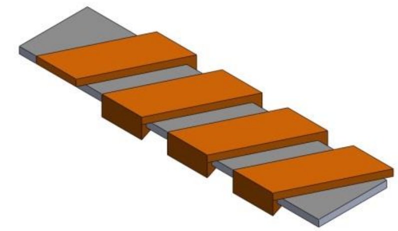
Racetrack



Toroid



Solenoid



Closed core	Yes	Yes	No
Core deposition steps	2	1	1
Magnetic vias	Yes	No	No
Compatible with uniaxial anisotropy	Yes	No	Yes

Pictures from “Integrating Magnetics for on-Chip Power: A Perspective”, C. R. Sullivan et al., IEEE trans on power electronics, 2013.