Projected Field Electromagnets for Controllable Magnetic Field at a Point

IEEE Magnetics SCV / SF Chapter

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GMW Associates

Presenter

Ian Walker
ian@gmw.com

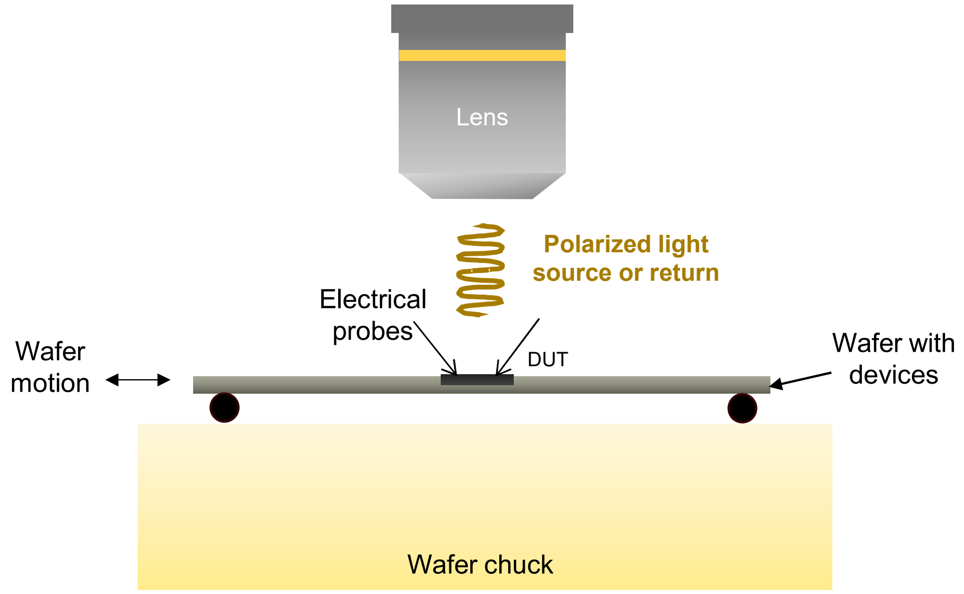
Contributors

Cerwyn Chiew
cerwyn@gmw.com

Tom King
tom@gmw.com

Testing magnetic devices at wafer level

Typical wafer probe station



Testing magnetic devices at wafer level

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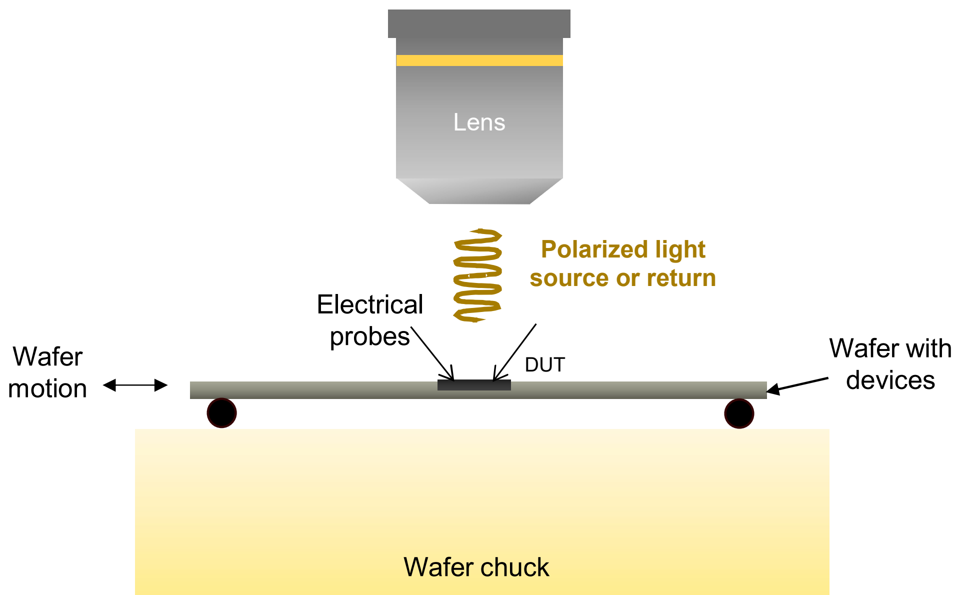
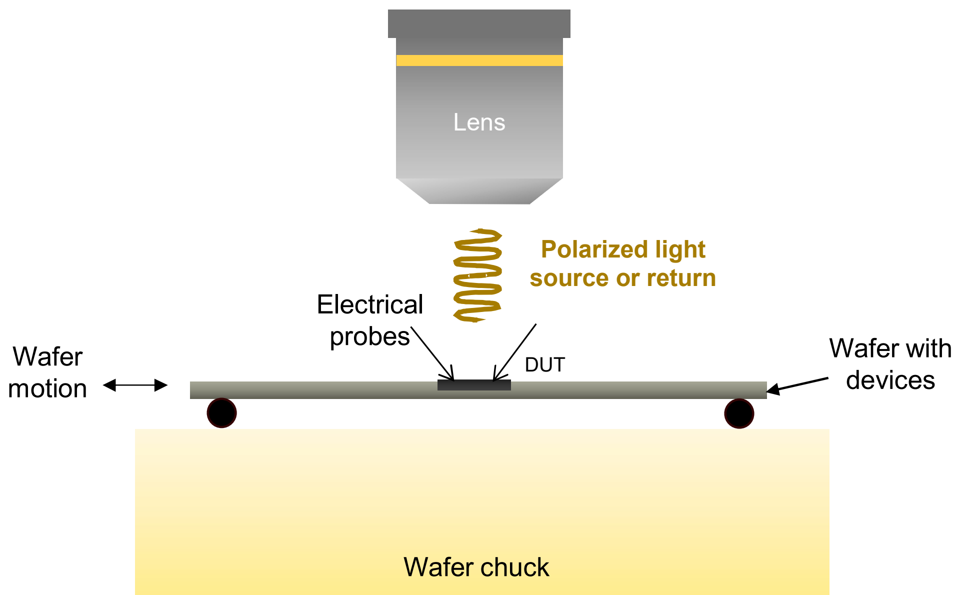


- Wafer size dominantly at 300mm but >300mm is possible in the future!
- Individual magnetic devices (MRAM, Spintronics) are getting smaller (0.2 ~2.0 mm)

Testing magnetic devices at wafer level

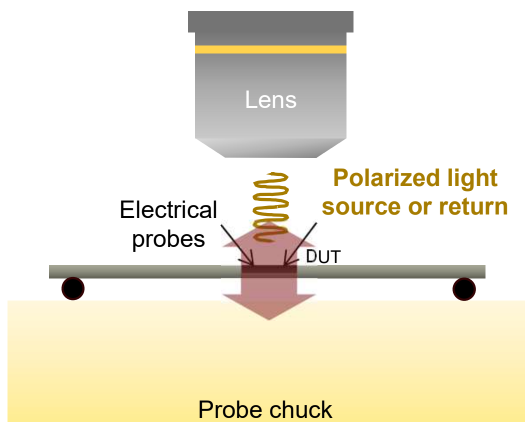
Typical wafer probe station



- Wafer size dominantly at 300mm but >300mm is possible in the future!
- Individual magnetic devices (MRAM, Spintronics) are getting smaller (0.2 ~2.0 mm)
- We can either test an array of devices or subset of devices.
- The following decision makes a huge difference in suitable magnet system solutions

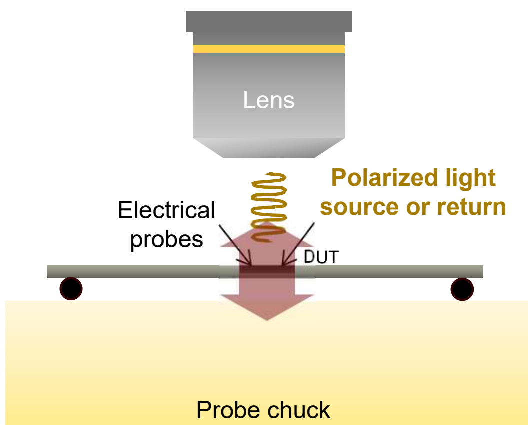
Testing magnetic devices at wafer level

Applying vertical magnetic field stimulus?

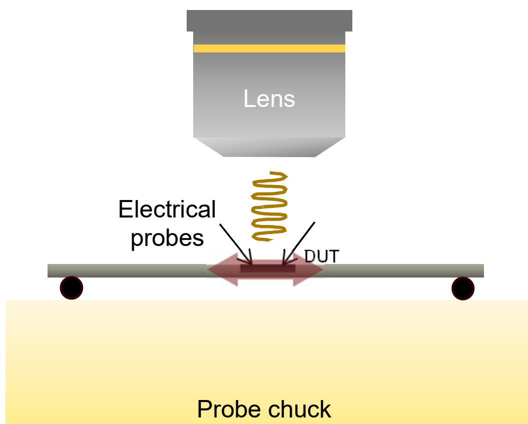


Testing magnetic devices at wafer level

Applying vertical magnetic field stimulus?

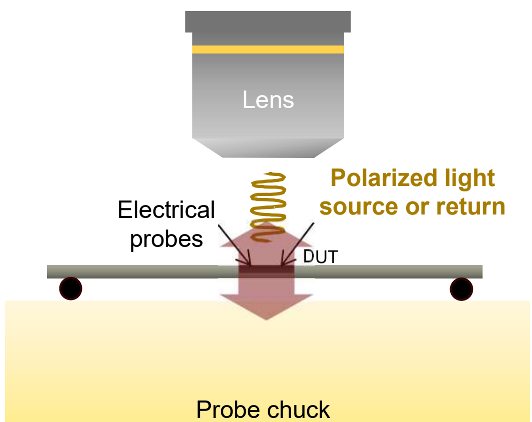


Applying In-Plane magnetic field stimulus?

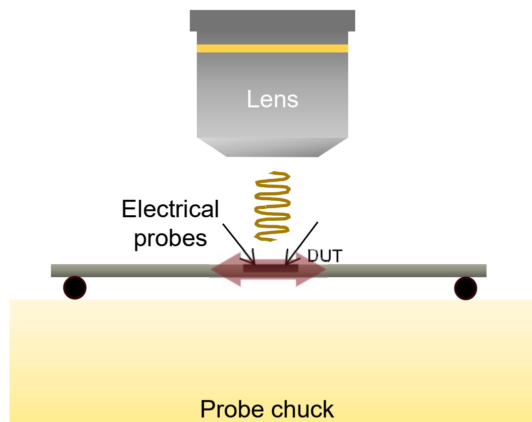


Testing magnetic devices at wafer level

Applying vertical magnetic field stimulus?



Applying In-Plane magnetic field stimulus?



- **Vertical & In-Plane** field strength (~100mT to 1T), uniformity requirement can vary by applications
- Permanent Magnet? – Could work but if varying field stimulus is needed with precise direction, control becomes challenging

In-plane magnetic stimulus on wafer with dipole EM?

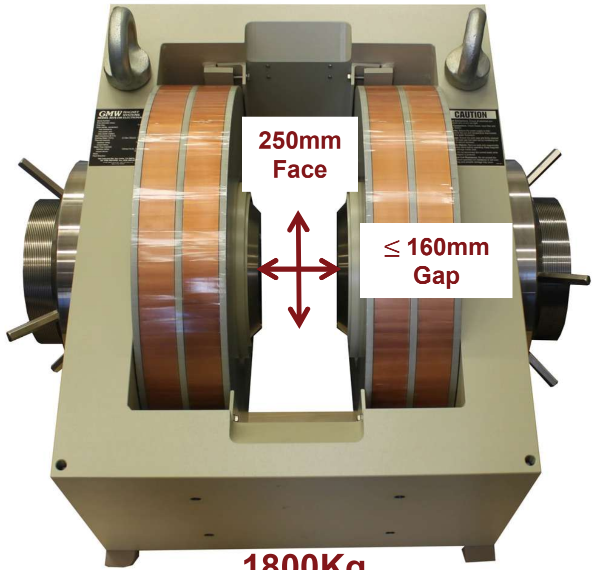
Projected field magnet test probe station system

In-plane magnetic stimulus on wafer with dipole EM?

Projected field magnet test probe station system

?

GMW 3474 – 140Amps Coil
10.6kW, DC to 2Hz



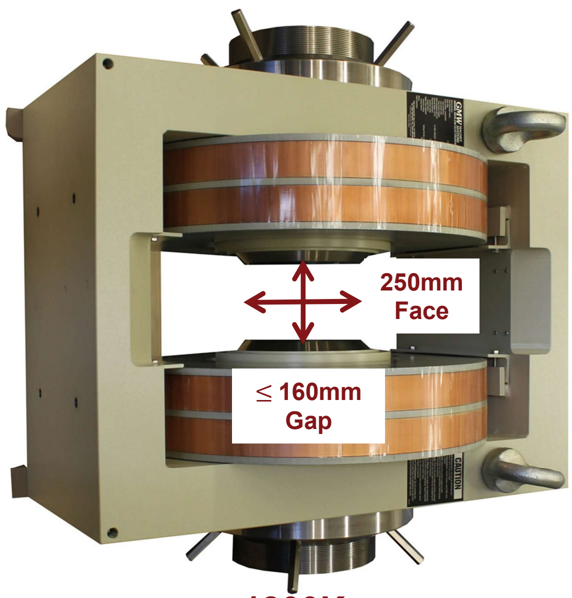
1800Kg

Vertical magnetic stimulus on wafer with dipole EM?

Projected field magnet test probe station system

?

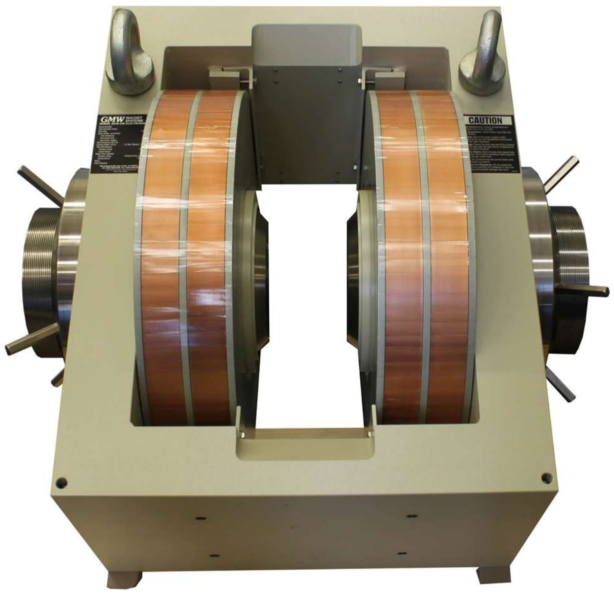
GMW 3474 – 140Amps Coil
10.6kW, DC to 2Hz



1800Kg

Applying magnetic stimulus on wafer with traditional dipole EM?

GMW 3474 – 140Amps Coil
10.6kW, DC to 2Hz

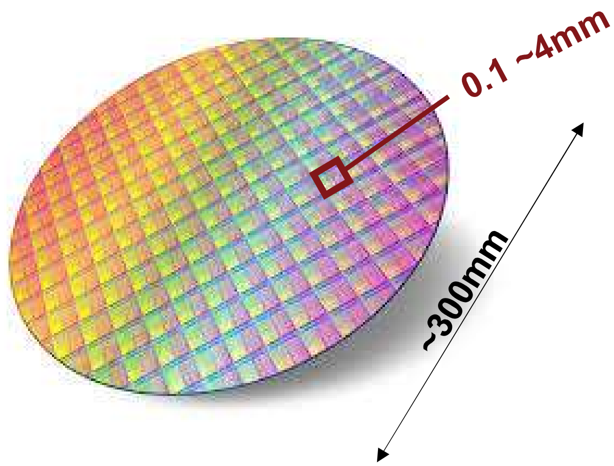


1800Kg

- Traditional wafer probe station mechanical setups are bulky
- Fitting the standard wafers, holder, & optical hardware in a dipole EM gap is not practical
- Any suitable dipole magnet system for providing required field magnitude or direction will be heavy, not benchtop size, and requires higher input power
- **DUT is much smaller than overall wafer size!**

Applying vertical magnetic stimulus on wafer (Alternative)

DUT is much smaller than overall wafer size



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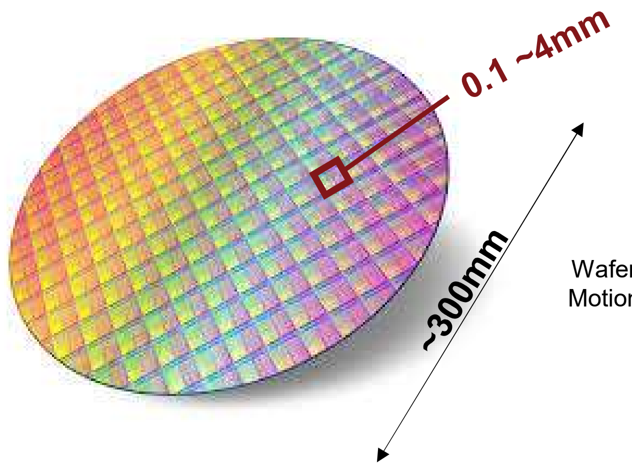
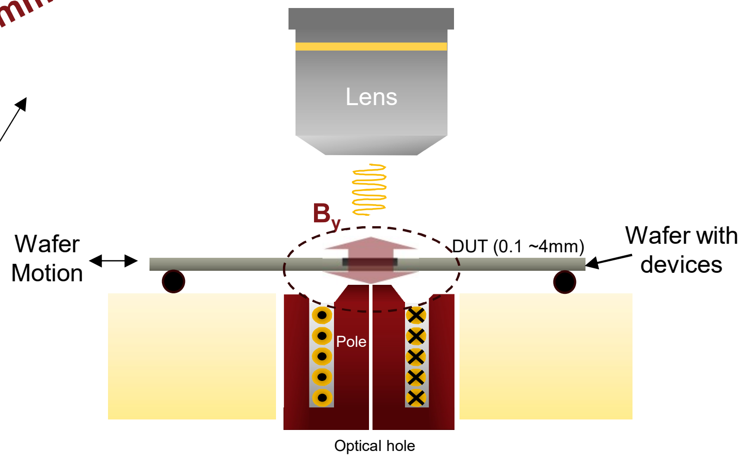


Apply vertical field stimulus at a point



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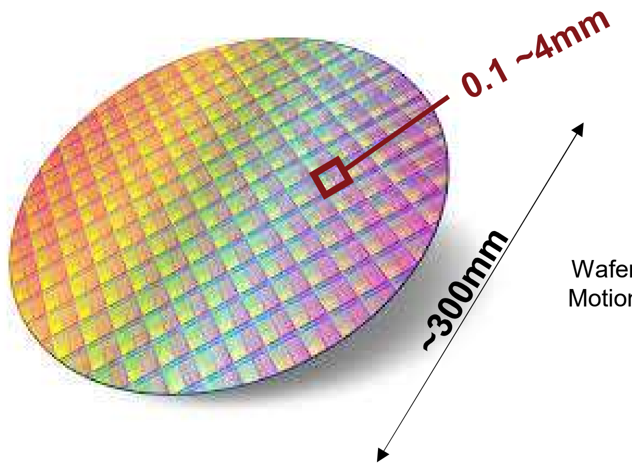

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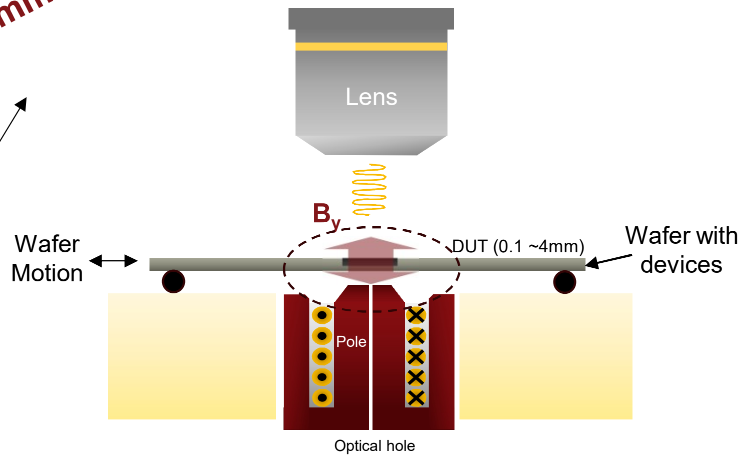
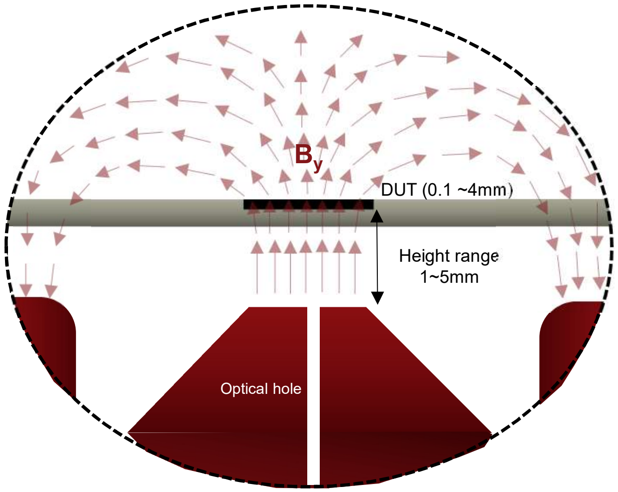


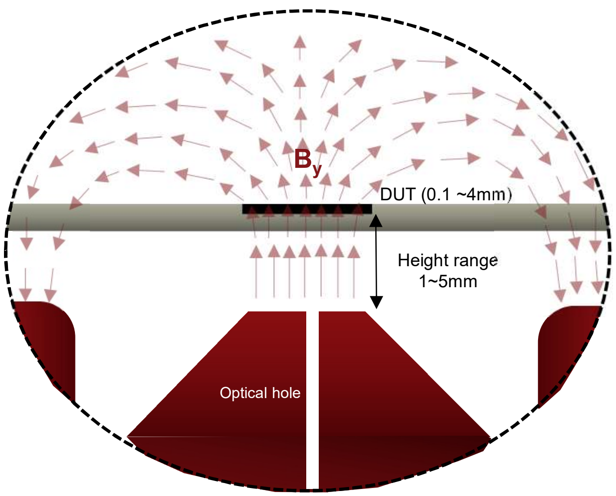
Use steel pole to precisely shape near fringe field



Only an Illustration

Applying vertical magnetic stimulus on wafer (Alternative)

Use steel pole to precisely shape near fringe field



Only an Illustration

Vertical field electromagnet

2.5Kg

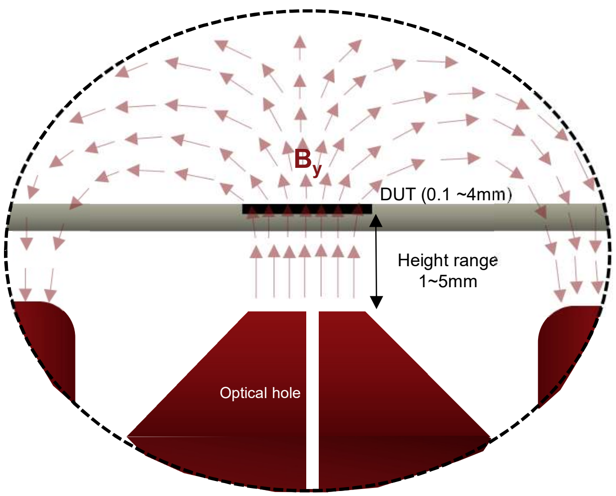
GMW 5203 – 63Amps Coil

1.1kW (Continuous)
3kW (Peak)
DC to 200Hz

Achievable peak field 1.2T

Applying vertical magnetic stimulus on wafer (Alternative)

Use steel pole to precisely shape near fringe field



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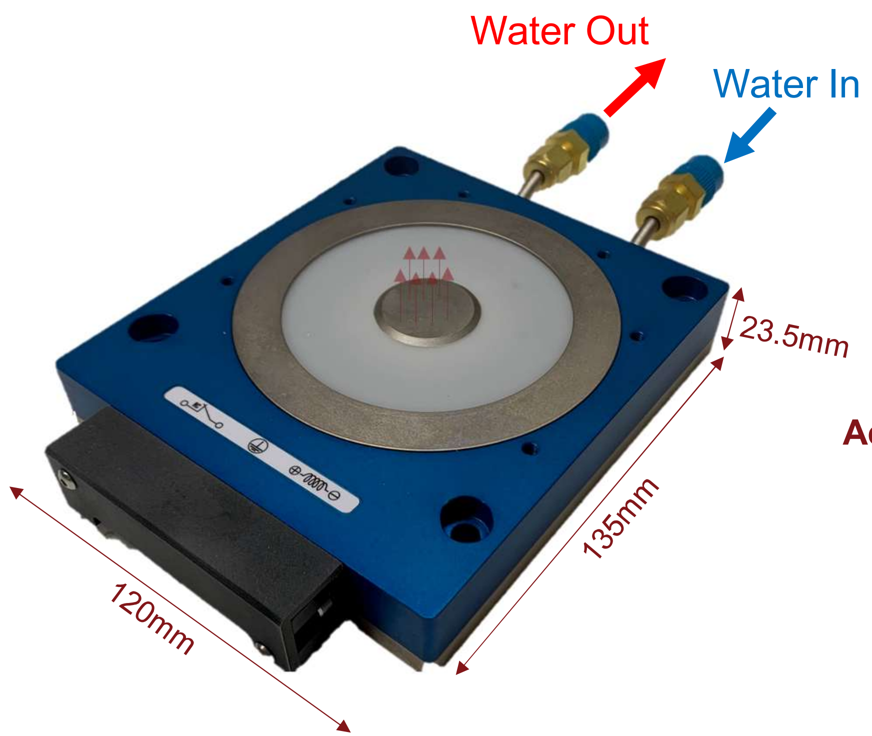
Vertical field electromagnet



2.0Kg

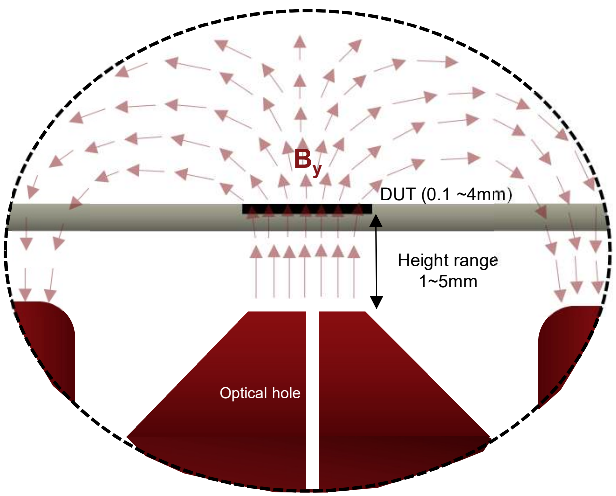
GMW 5205T – 20Amps Coil

35W (Continuous)
110W (Peak)
DC to 200Hz

Achievable peak field 0.2T

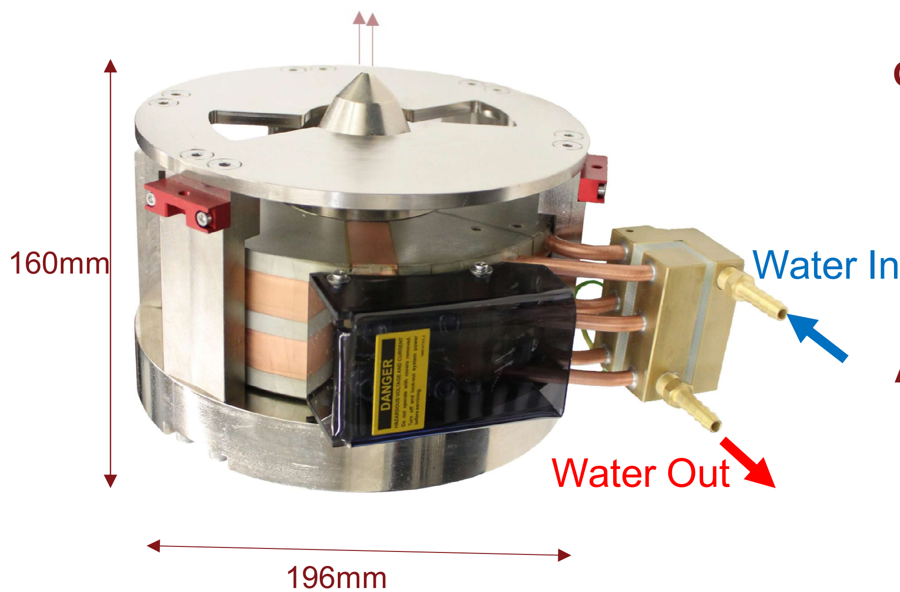
Applying vertical magnetic stimulus on wafer (Alternative)

Use steel pole to precisely shape near fringe field



Only an Illustration

Vertical field electromagnet



20.0Kg

GMW 5207 – 37 Amps Coil

1kW (Continuous)
6kW (Peak)
DC to 10Hz

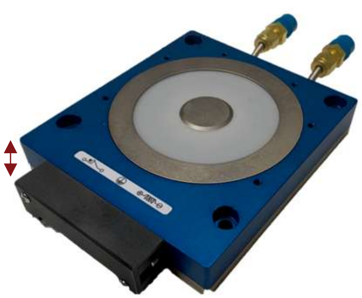
Achievable peak field 1.8T

Vertical projected field magnet size overview

5205T

B_{peak} = 0.2T

23.5mm



5203

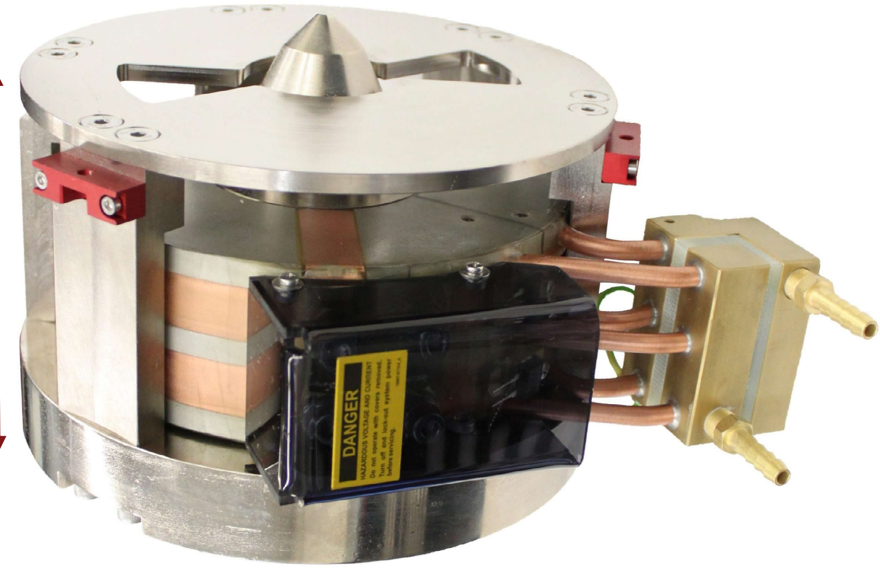
B_{peak} = 1.2T

123.5mm

5207

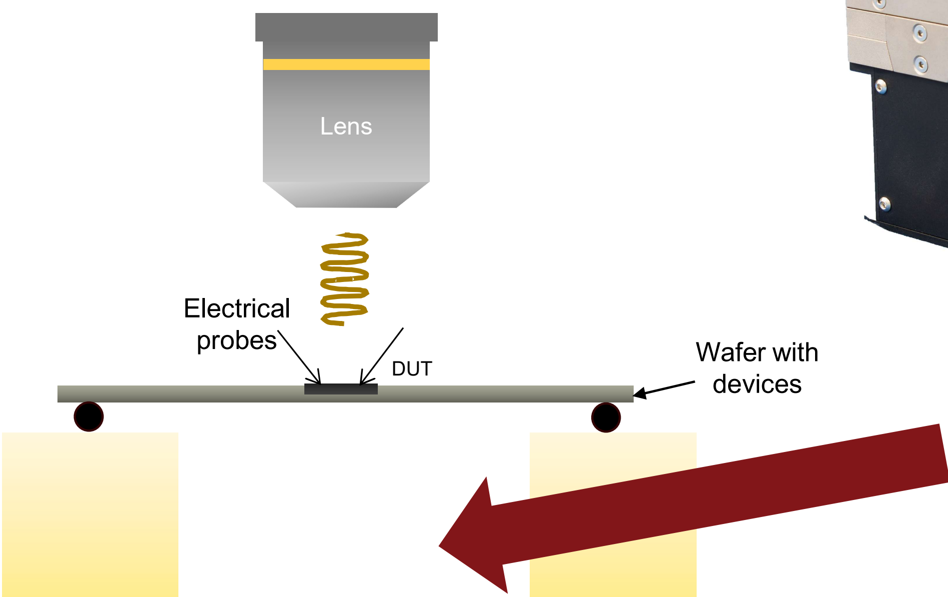
B_{peak} = 1.8T

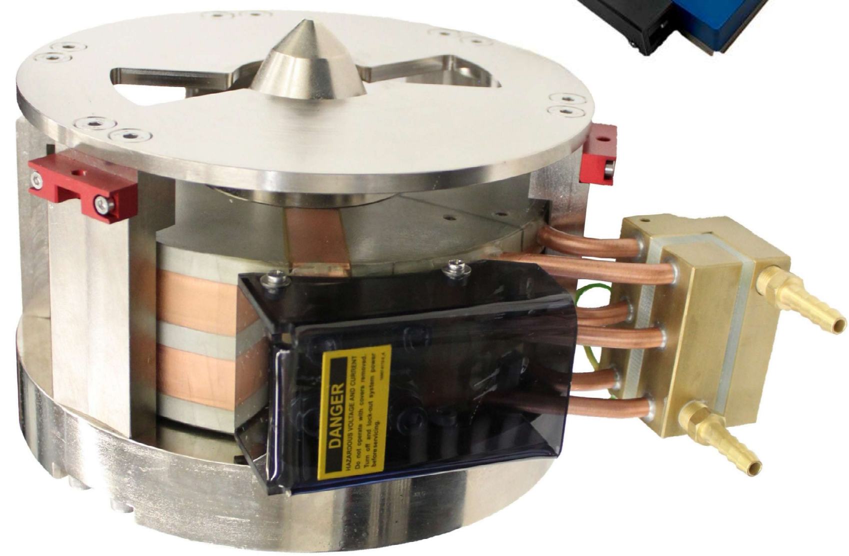
160mm



Vertical projected field magnet size overview

Typical wafer probe station



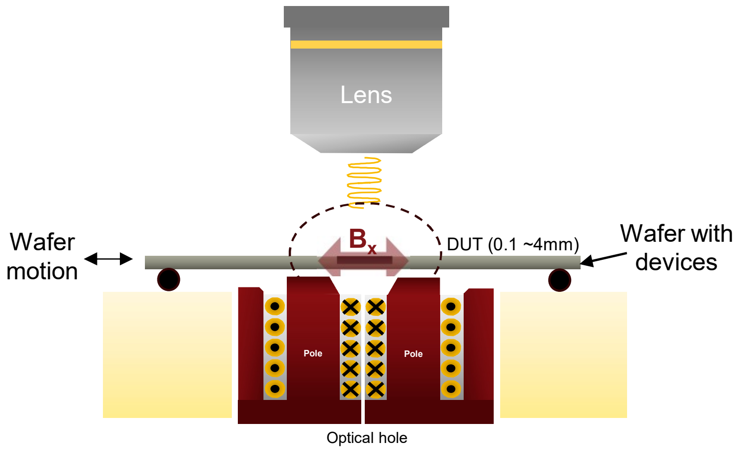


Min field, space available, duty cycle, uniformity area ???

Applying vertical magnetic stimulus on wafer (Probe System)

Applying magnetic stimulus on wafer (Alternative)

Apply In-Plane field stimulus at a point



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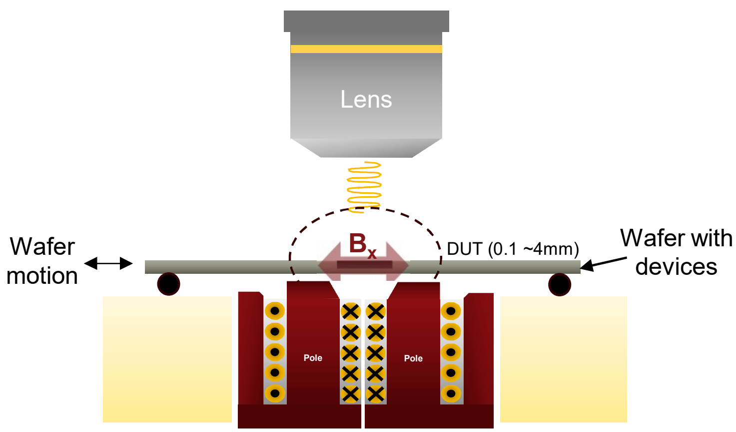
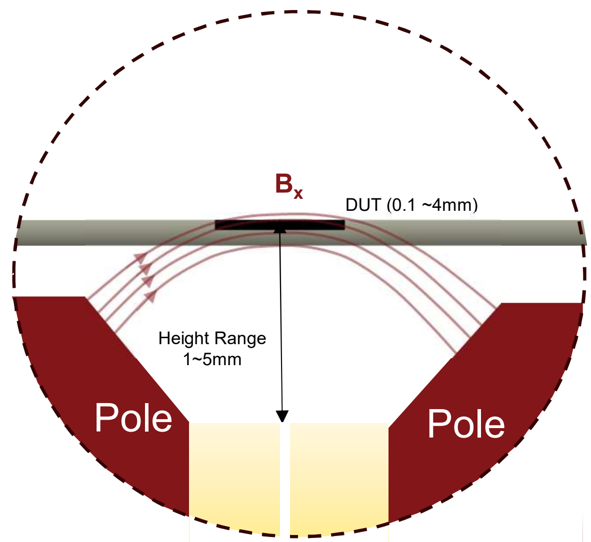


Use pole pair to precisely shape In-Plane fringe field



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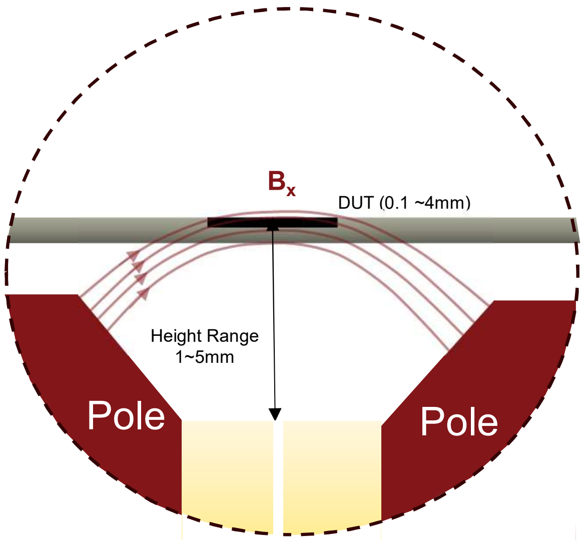


Optical hole access

In-Plane field electromagnet

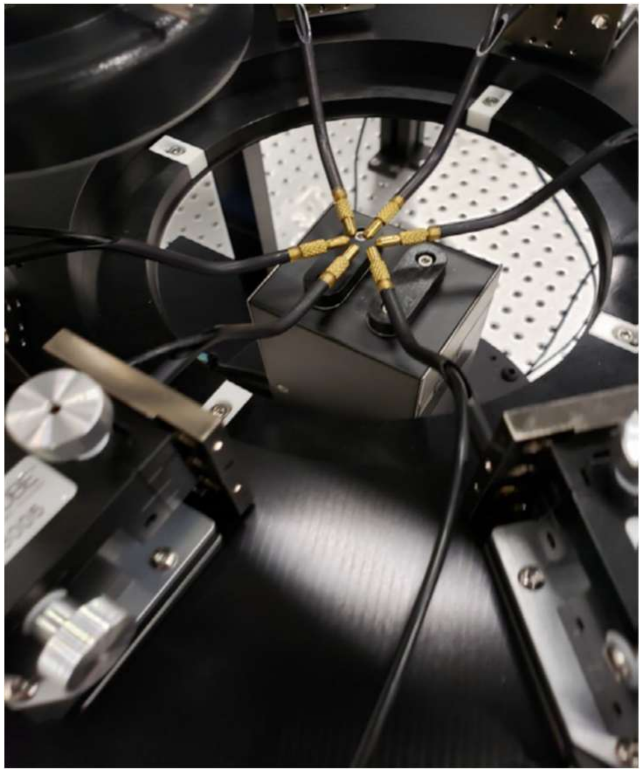
GMW 5201 – 5Amps Coil

25W (Continuous)
400W (Peak)
DC to 200Hz

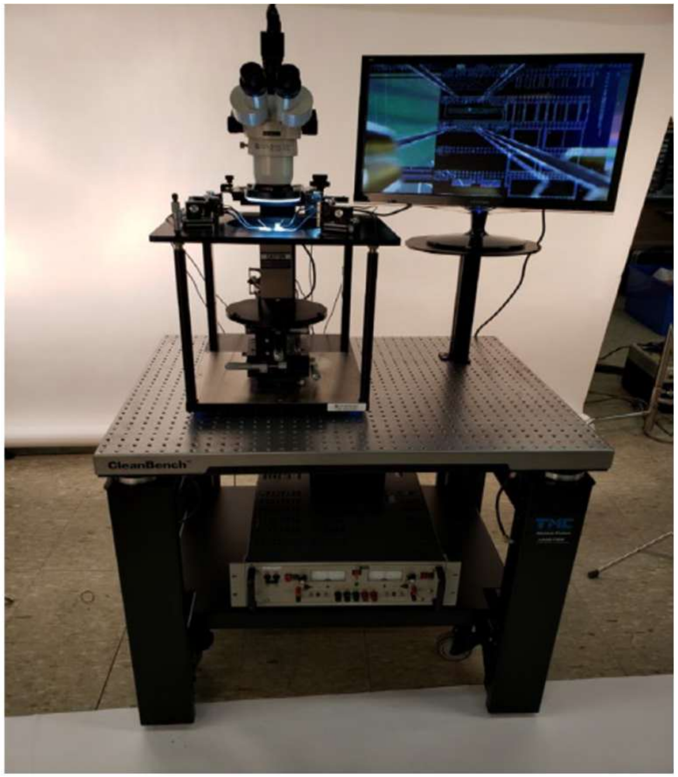
2.1Kg

Applying horizontal magnetic stimulus on wafer (Probe System)

Apply In-plane field Stimulus at a POINT!!!



5201 Magnet Integrated probe station



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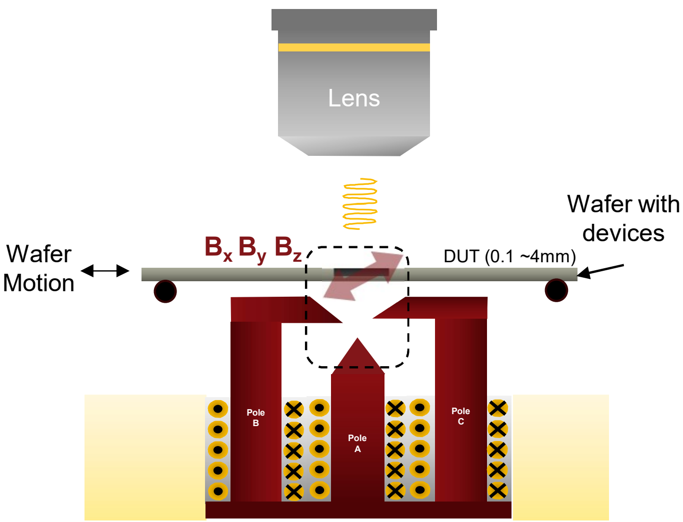
Applying vector magnetic stimulus on wafer

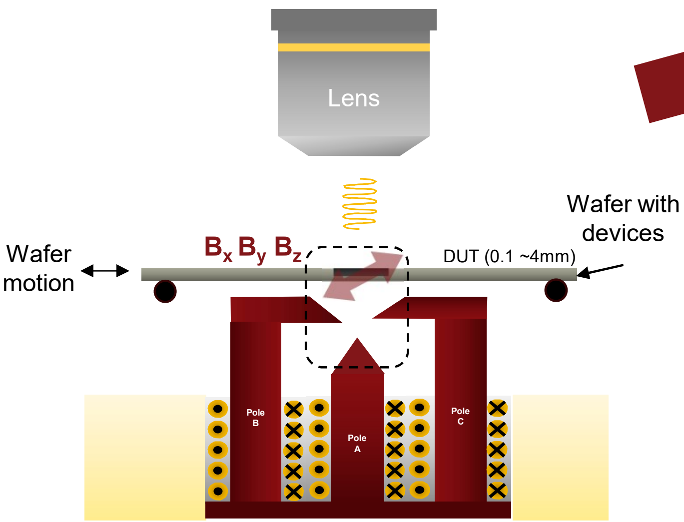
Apply vector field Stimulus at a point



3 Poles & 3 independent coils oriented 120deg circularly apart

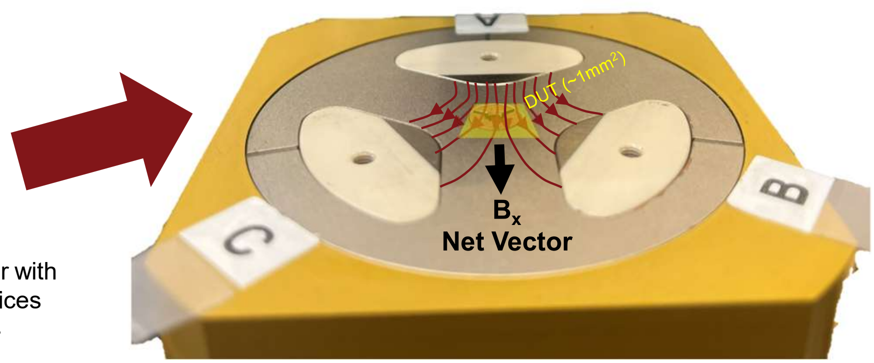
Applying vector magnetic stimulus on wafer

Apply vector field Stimulus at a point



3 Poles & 3 independent coils oriented 120deg circularly apart

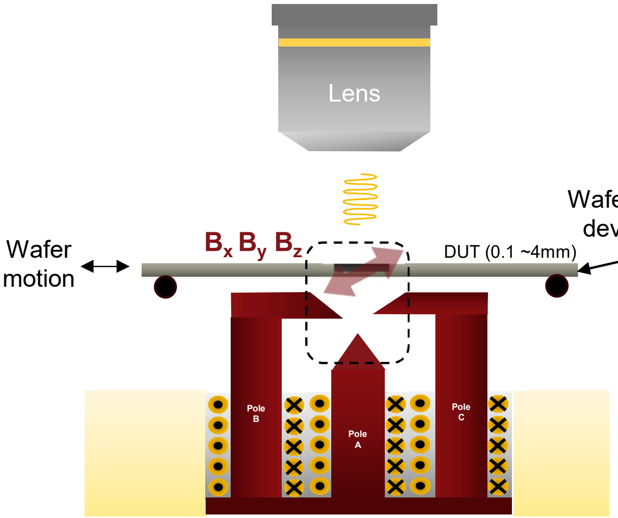
5204 projected field electromagnet



Illustrated field lines

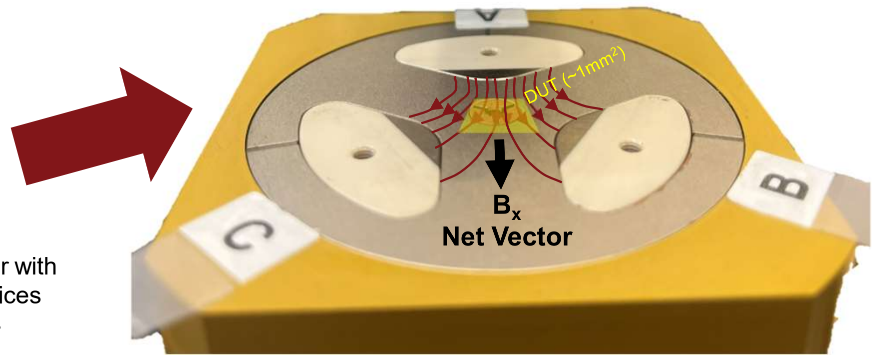
Applying vector magnetic stimulus on wafer

Apply vector field
Stimulus at a point



3 Poles & 3 independent coils oriented 120deg circularly apart

5204 projected field electromagnet



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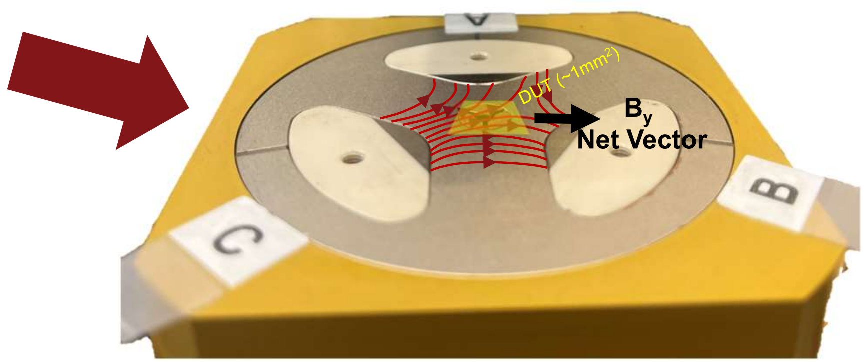
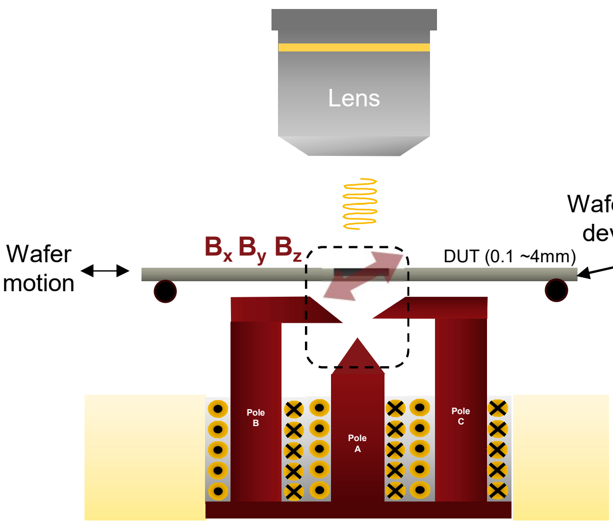


Applying vector magnetic stimulus on wafer

Apply vector field Stimulus at a point



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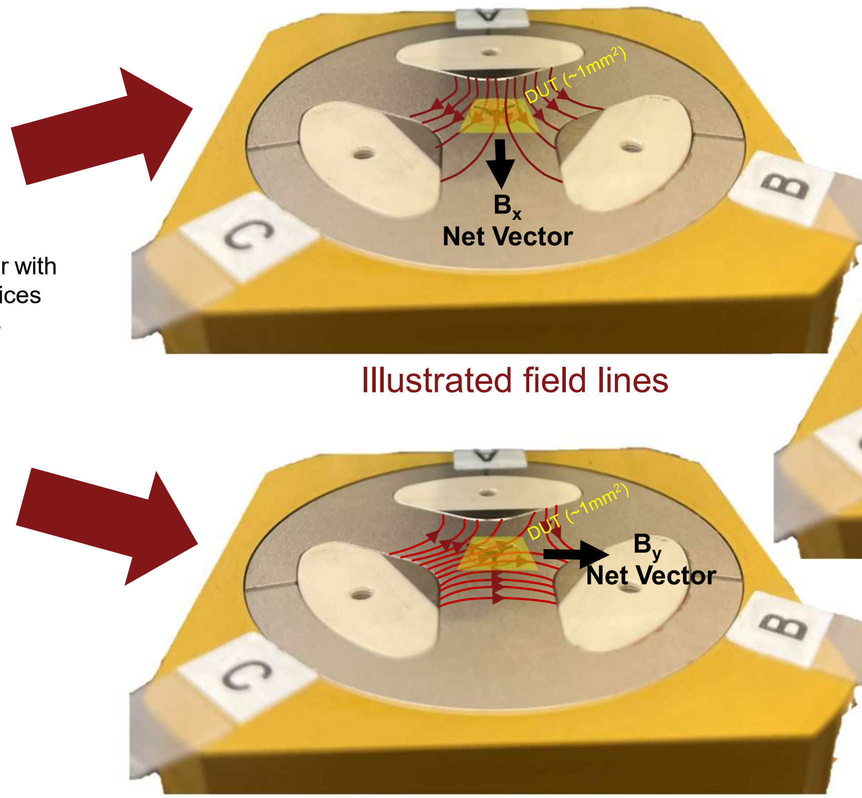
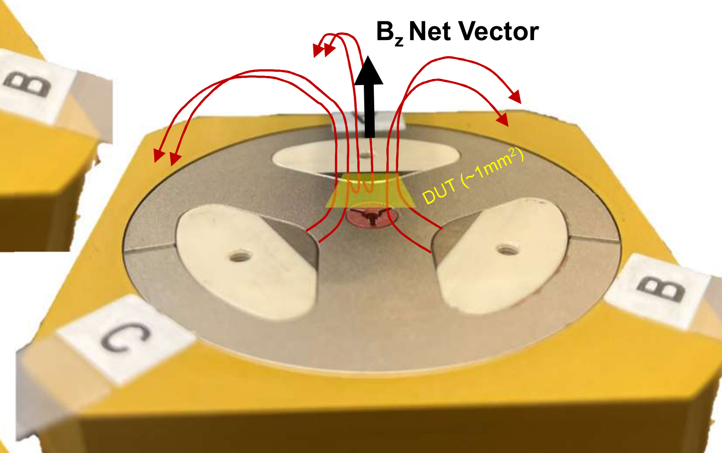
5204 projected field electromagnet



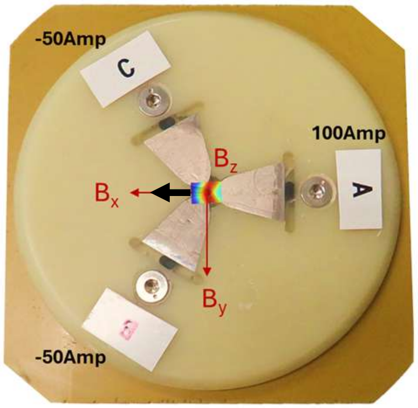


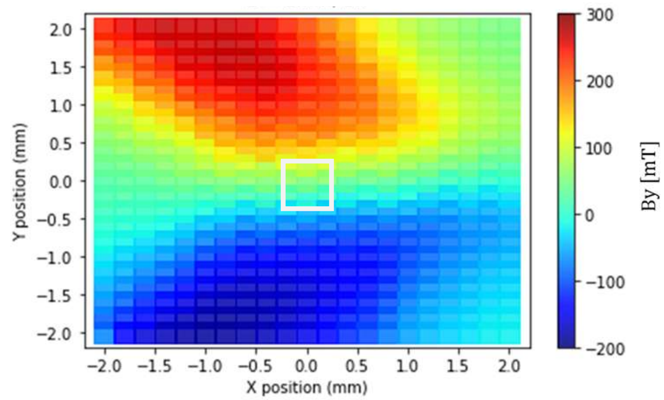
GMW 5204 – 63Amps Coil

175W / coil (Continuous)
450W / coil (Peak)
DC to 200Hz

2.5Kg

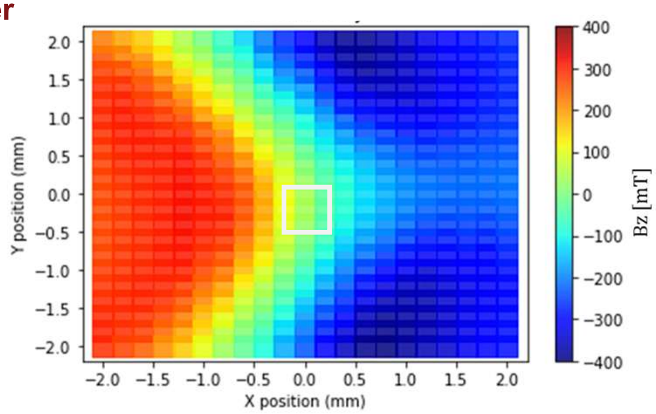
Applying vector magnetic stimulus on wafer

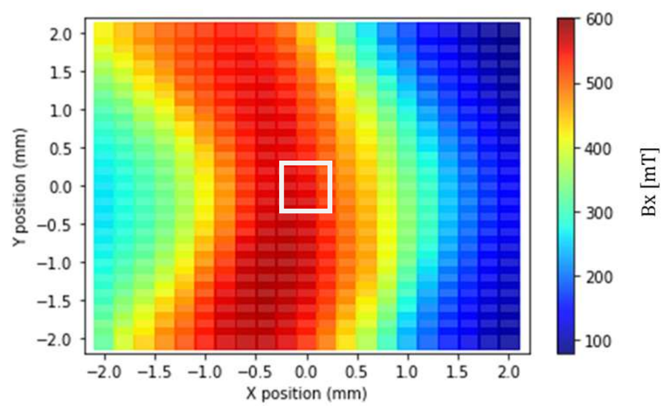




How big is the point? (working area)

Uniformity is better at higher height but lower peak field



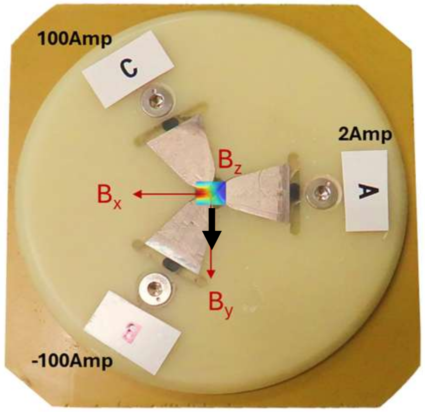


B_x = 600mT @ Z = 1mm

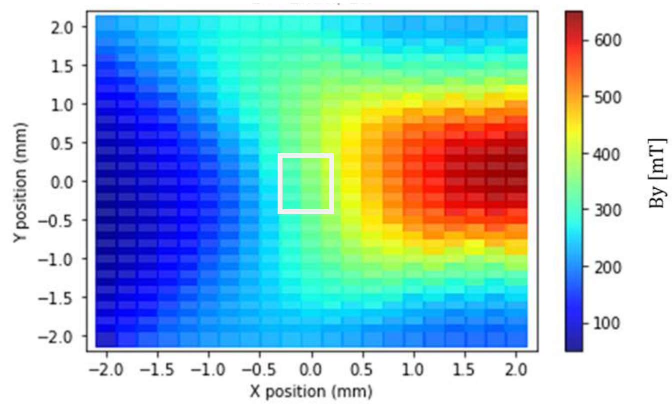
Applying vector magnetic stimulus on wafer

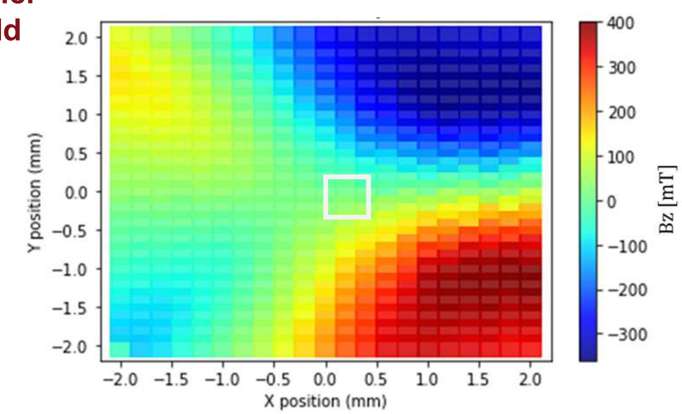
How big is the point? (working area)

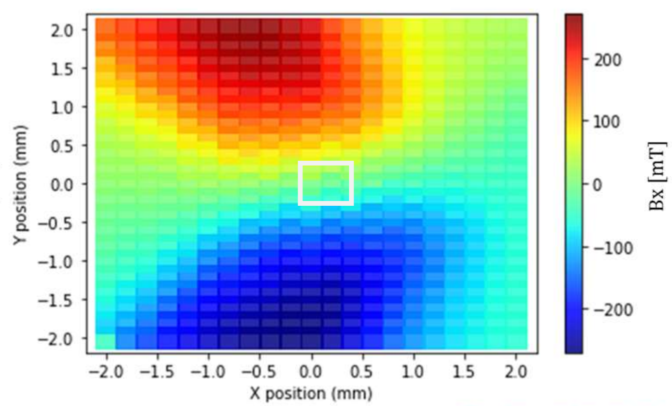
Uniformity is better at higher height but lower peak field



B_y = 300mT @ Z = 1mm

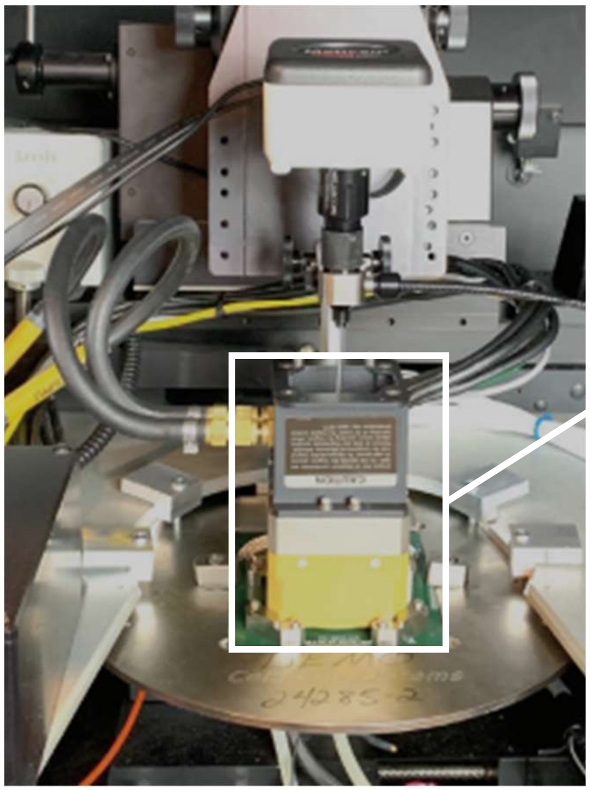




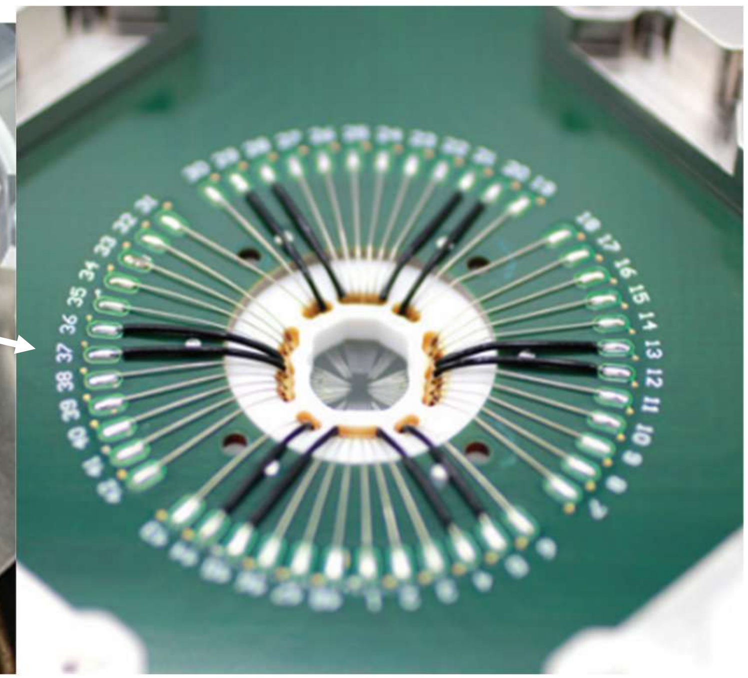


Applying vector magnetic stimulus on wafer (Probe System)

Projected vector magnet probe station

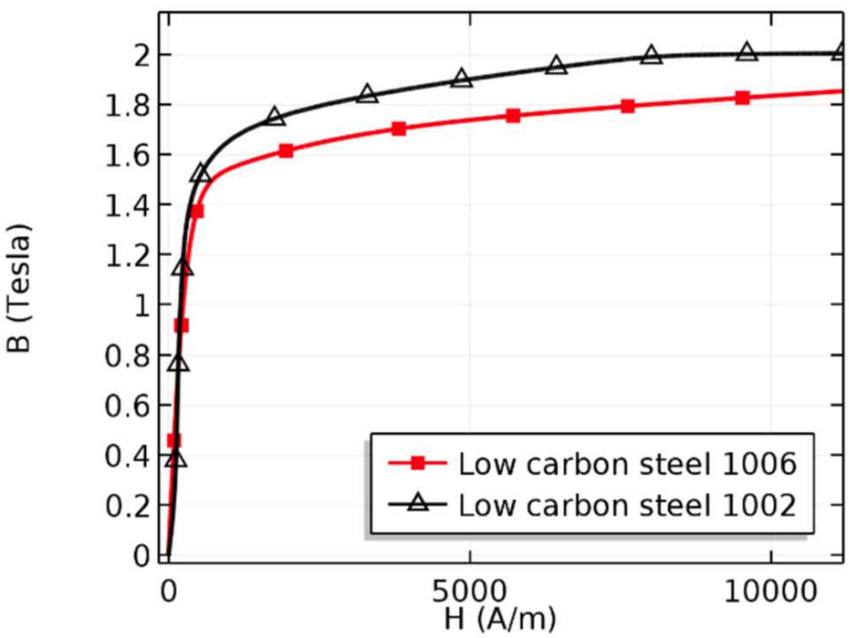


Probe card



B vs H curve of low carbon steel & permendur

Steel as lens focusing magnetic flux



Azad Ali et al., Sensors, 21(16):5539 (2021)

https://www.femm.info/wiki/softmagneticmaterials

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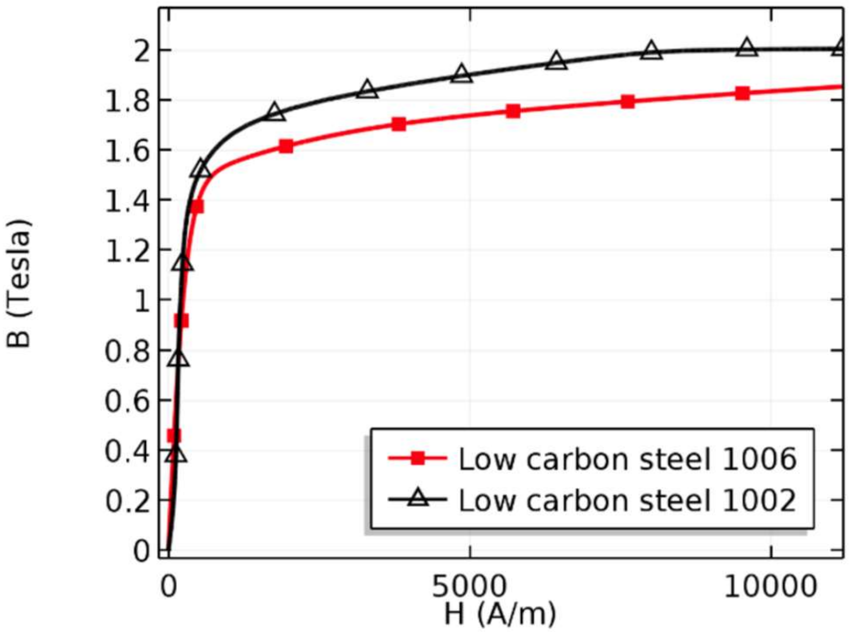
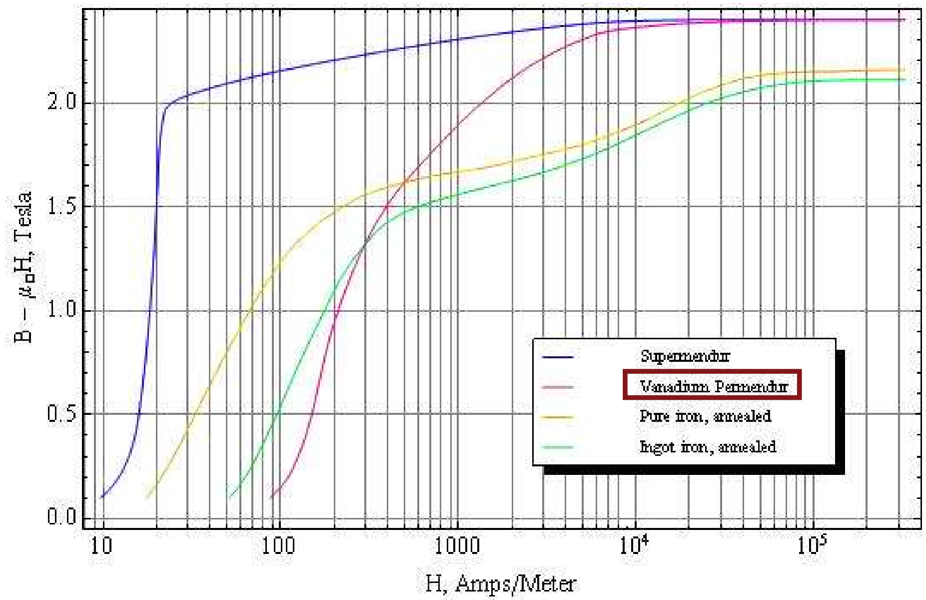


Permendur as additional lens focusing magnetic flux



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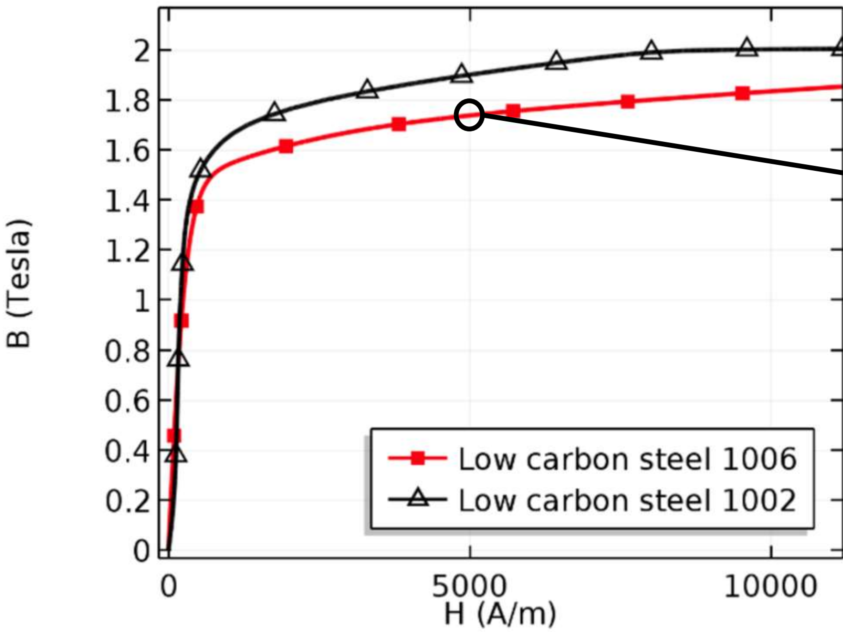
B vs H curve of low carbon steel & permendur

Steel as lens focusing magnetic flux

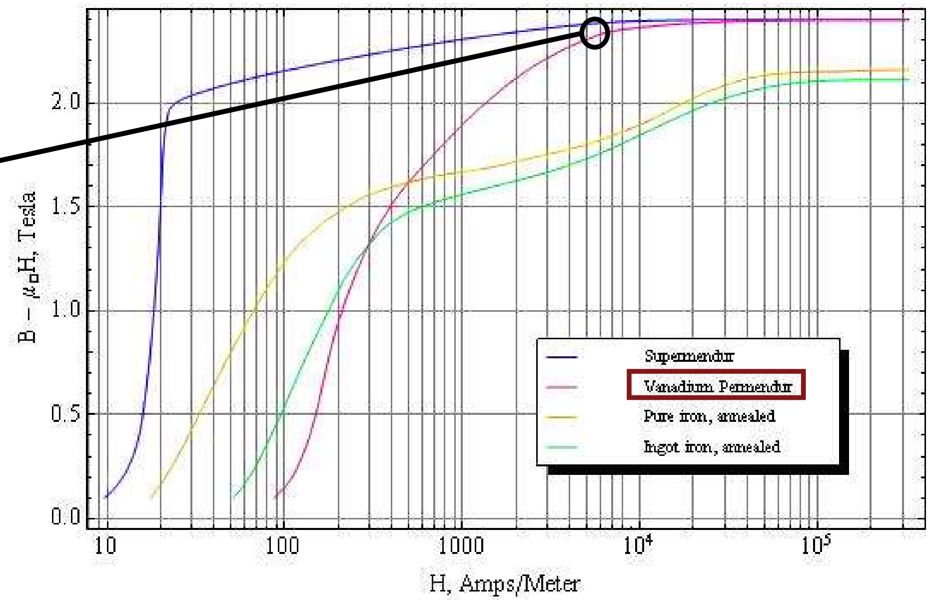


@ H = 5000A/m

1006:
B ~1.7T
(Saturated)

Permendur:
B~2.3T
(Near Saturation)

Permendur as additional lens focusing magnetic flux



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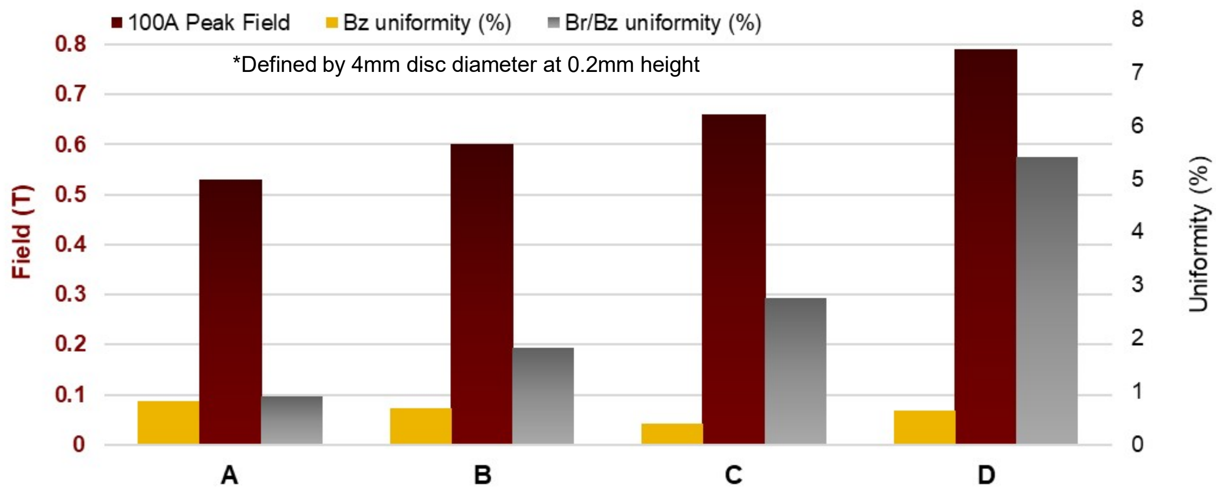
Vertical field electromagnet (5203)

All Permendur

Pole swaps - Max Field & uniformity adjustability



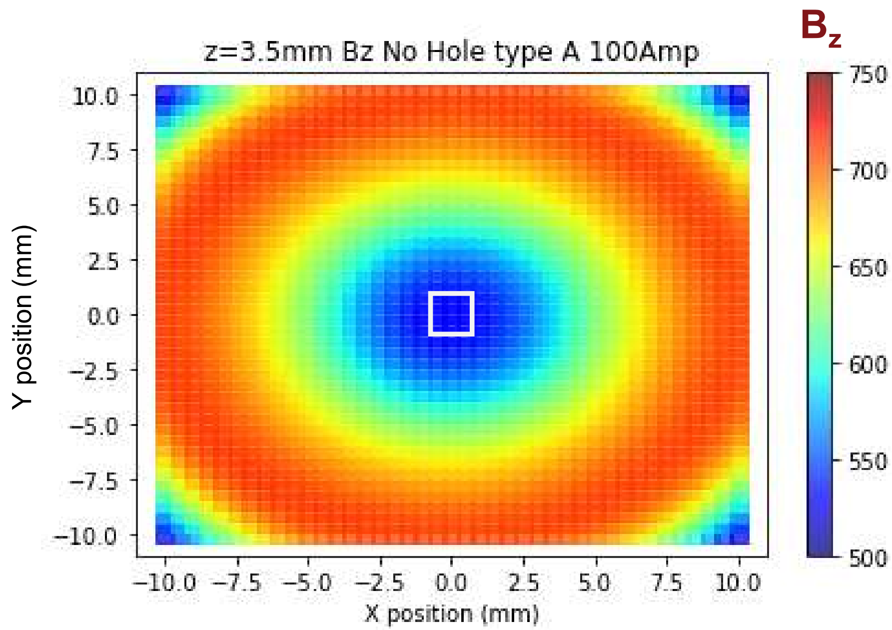
Standard

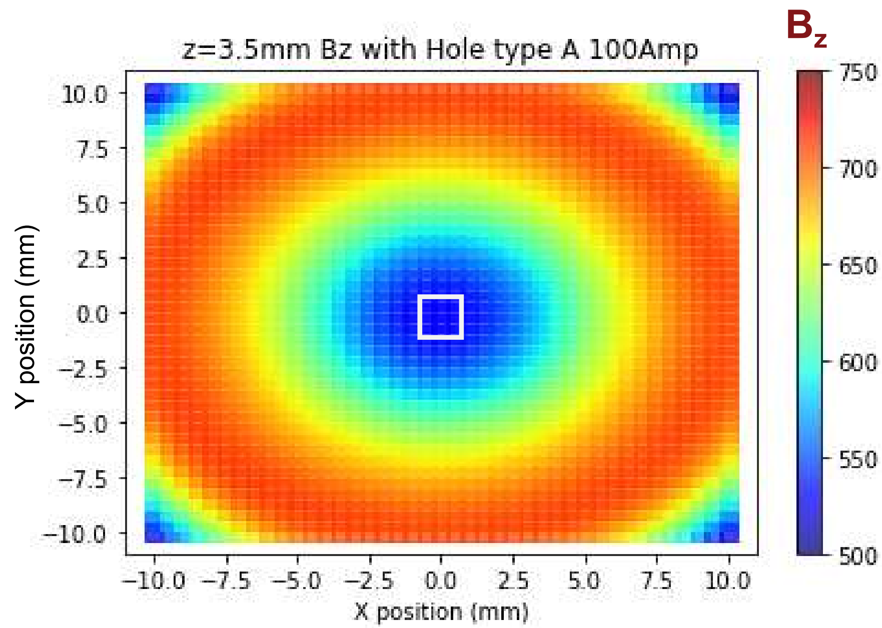
GMW Associates

Axial hole vs no hole on pole effects on field?

2mm diameter axial hole

2mm Axial Hole

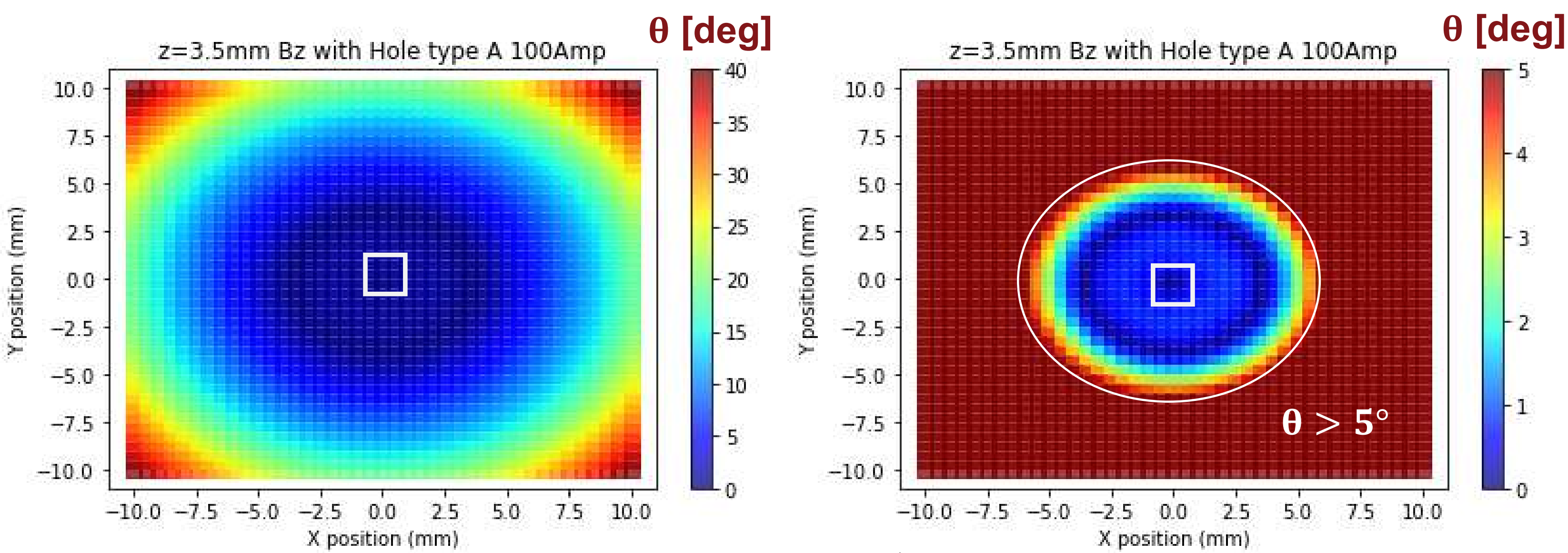


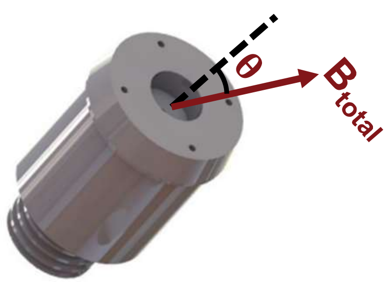


Unless DUT is near axial hole, peak field & uniformity are unaffected

Axial hole vs no hole on pole effects on field?

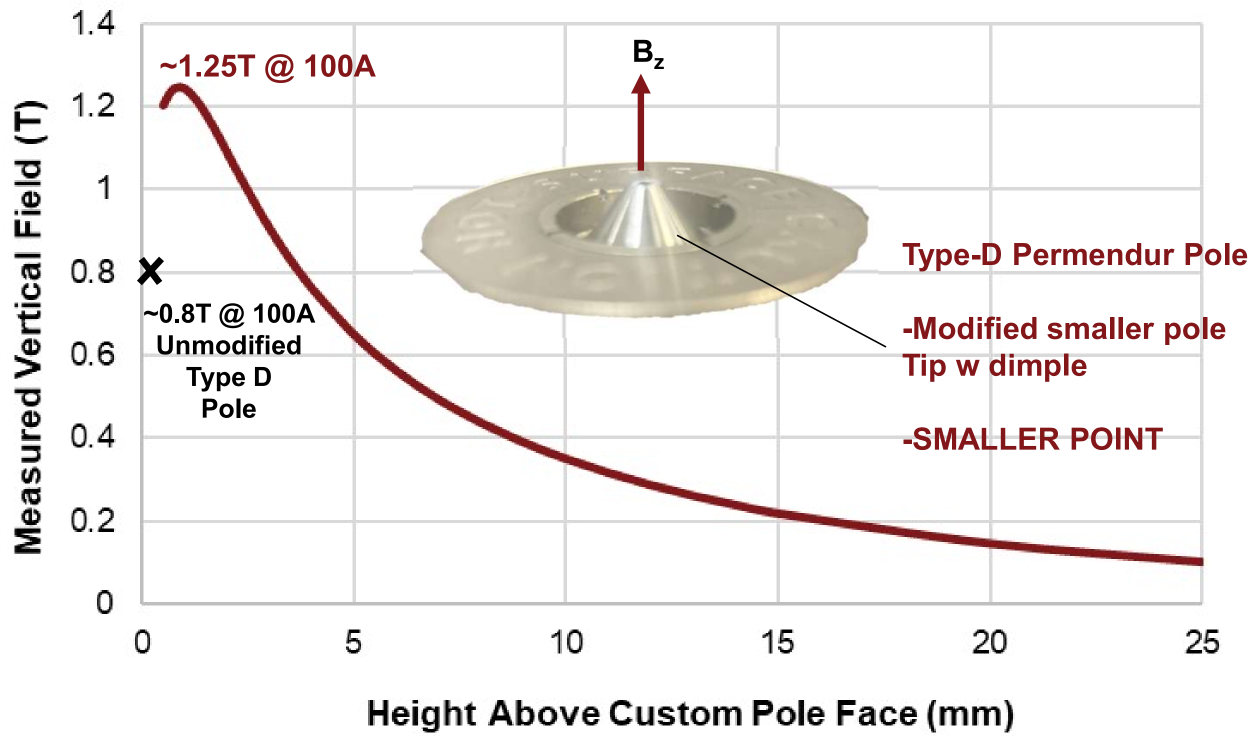
1mm diameter axial hole





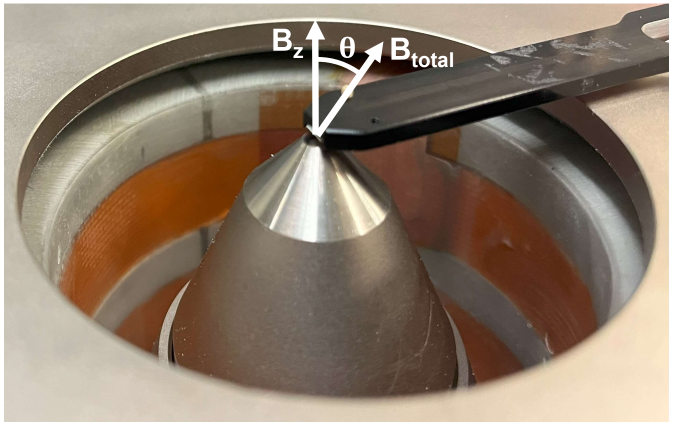
Vertical field electromagnet (5203 custom pole example)

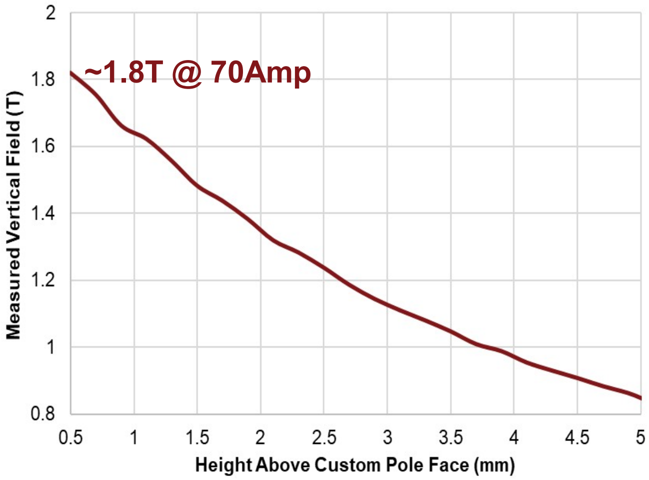
Customized pole – Optimize max. field at small DUT and target height

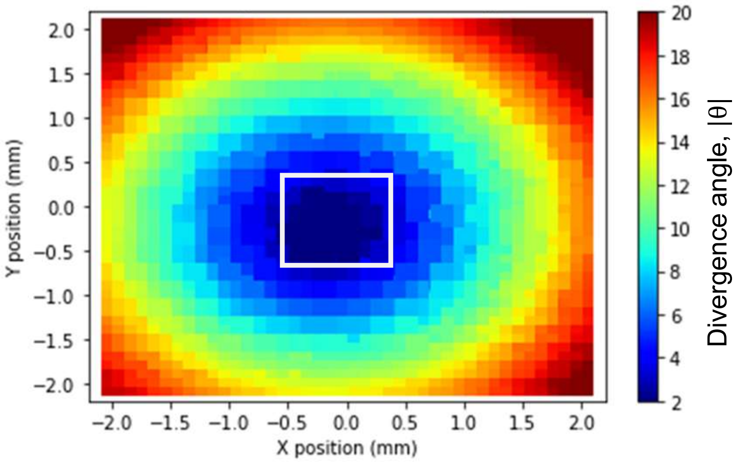


Vertical field electromagnet (5207 custom pole example)

Custom composite permendur / Steel pole – Maximize field & uniformity at target area



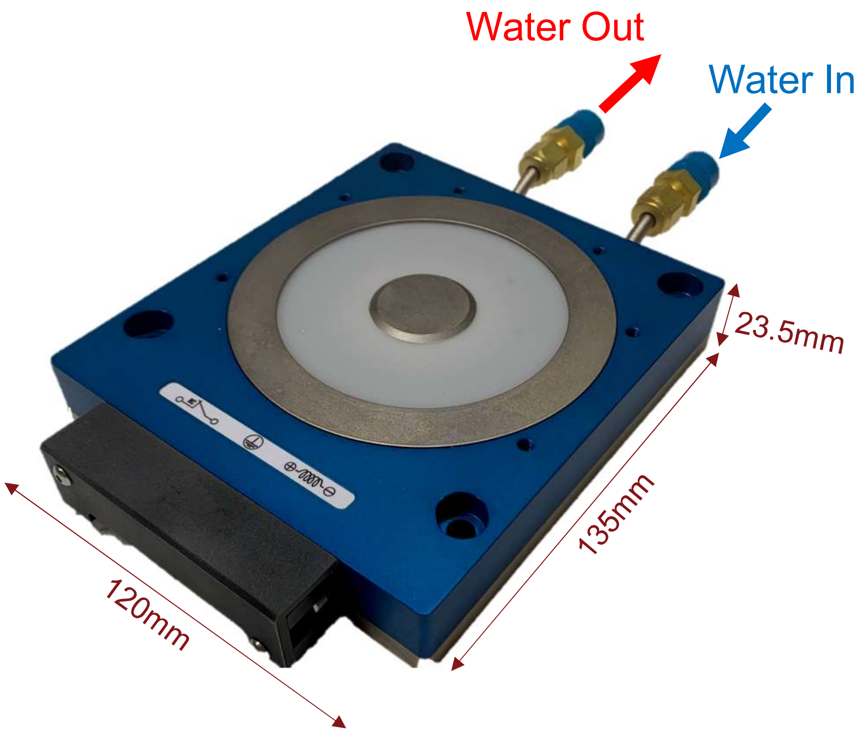




GMW Associates

Max field vs work time of projected field magnet

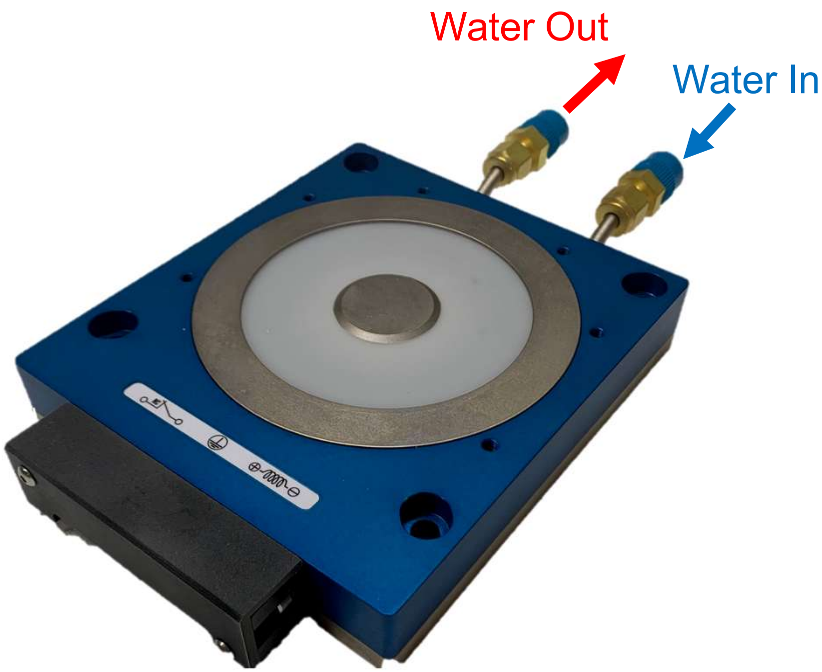
Thin profile projected field magnet (5205T)

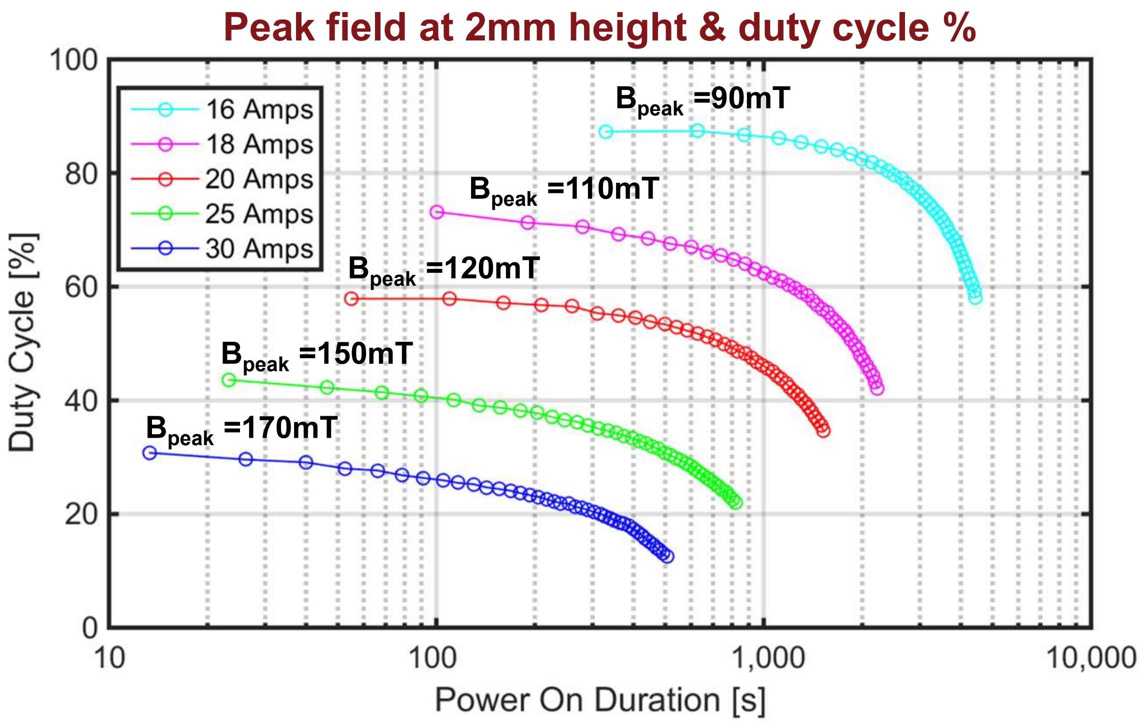


Higher peak field → **Higher current** → ***Loss*** **(I^2R)** → **Limited work time**

Max field vs duty cycle of projected field magnet

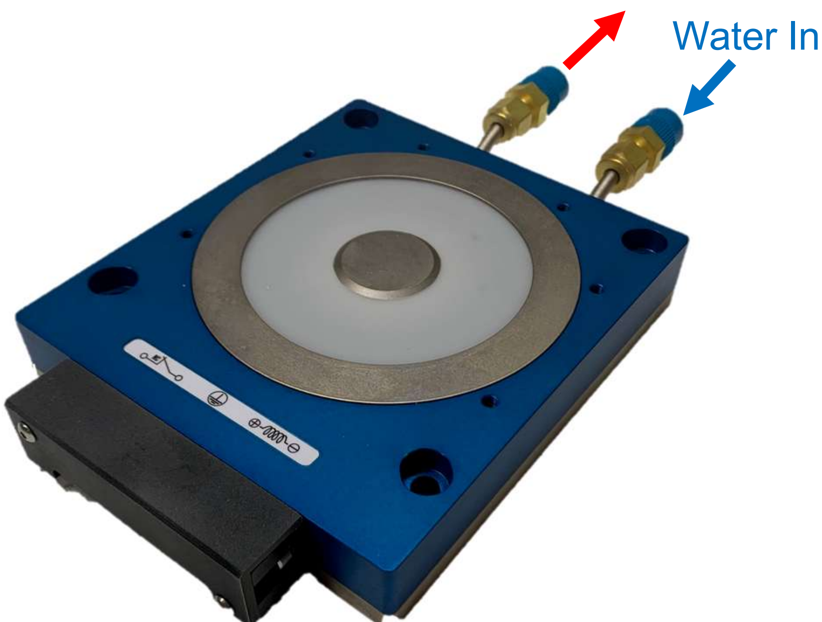
Thin profile projected field magnet (5205T)

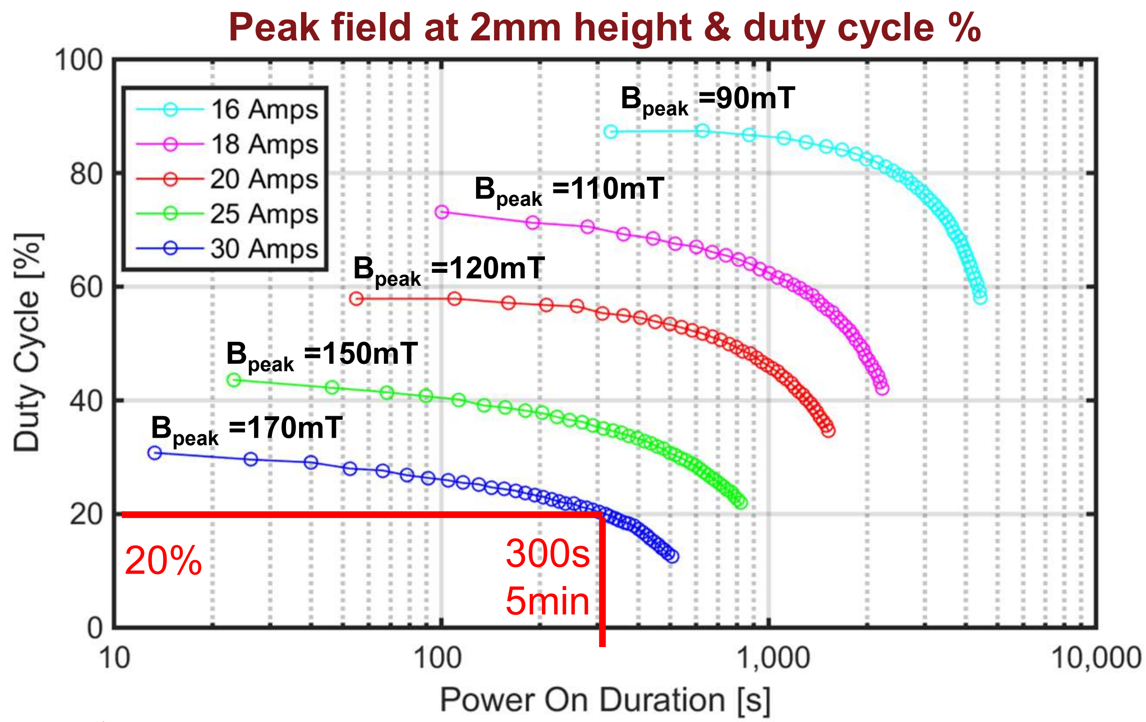




Max field vs duty cycle of projected field magnet

Thin profile projected field magnet (5205T)



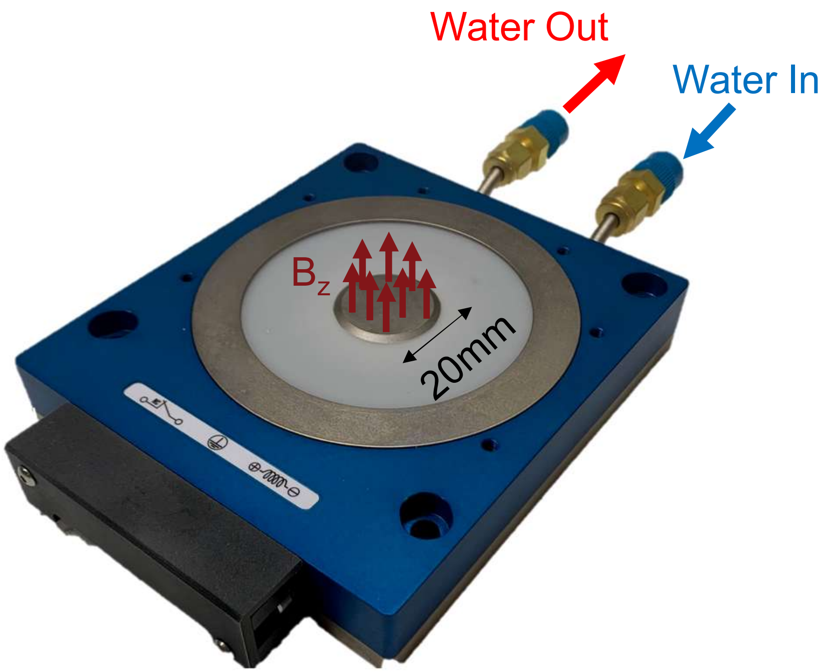


Total cycle (s) = $300s \times \frac{1}{0.2} = 1500s = 25min$

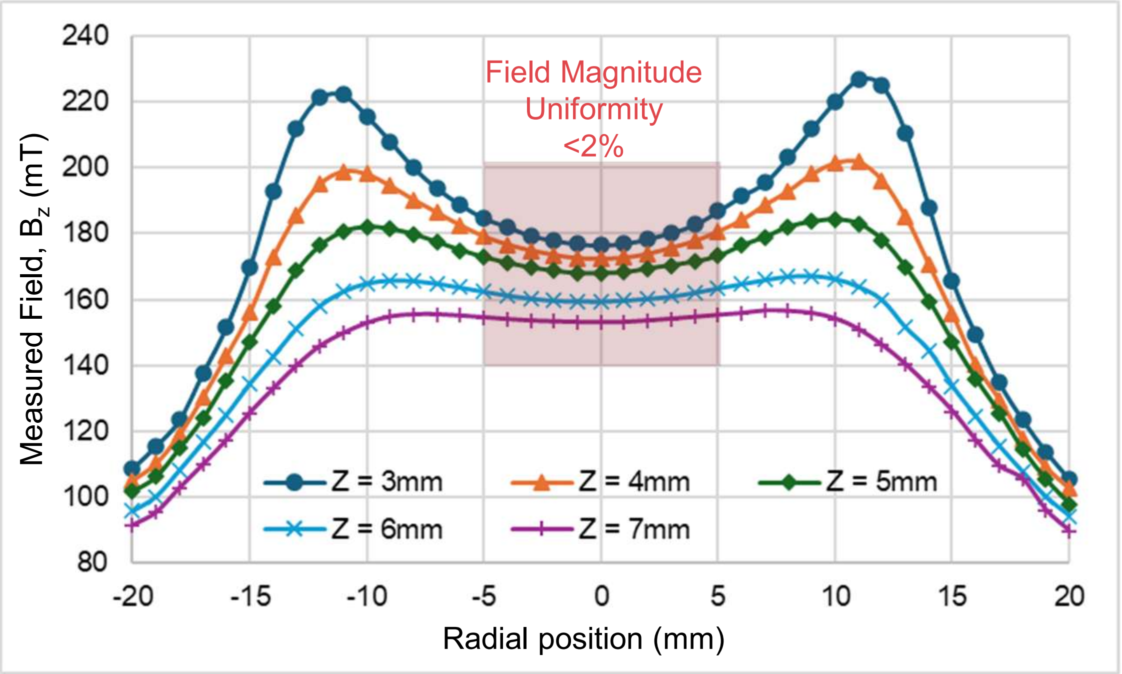
Cooling time (s) = Total cycle (s) – Power On (s) = 20min

Max field & work area of projected field magnet

Thin profile projected field magnet (5205T)

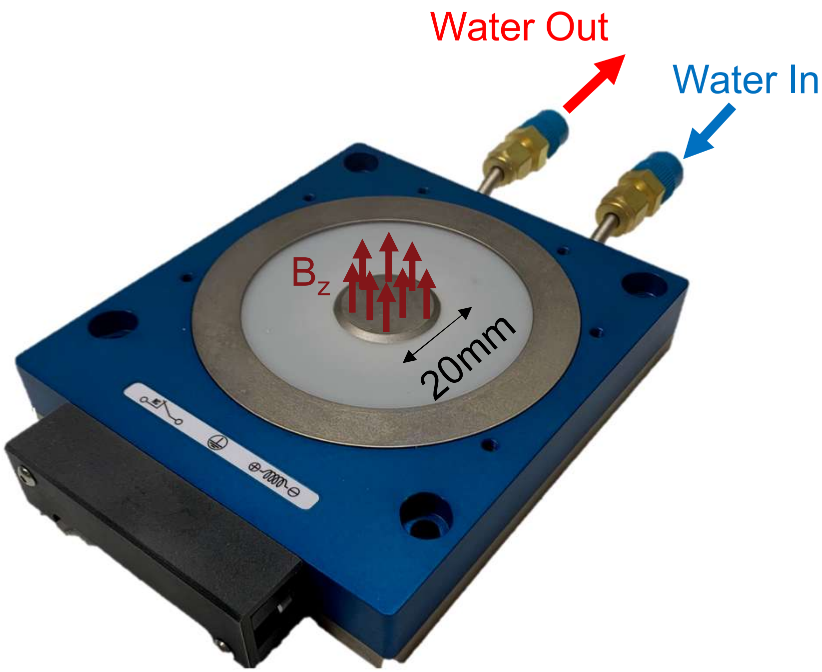


Working area of peak vertical field (30A)

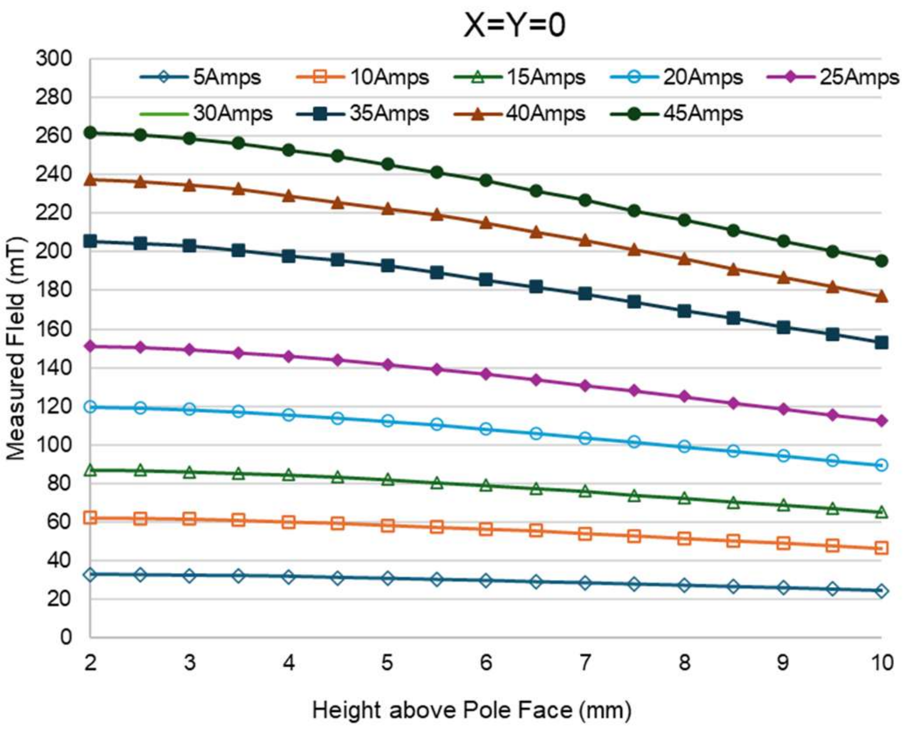


Max field & work height of projected field magnet

Thin profile projected field magnet (5205T)



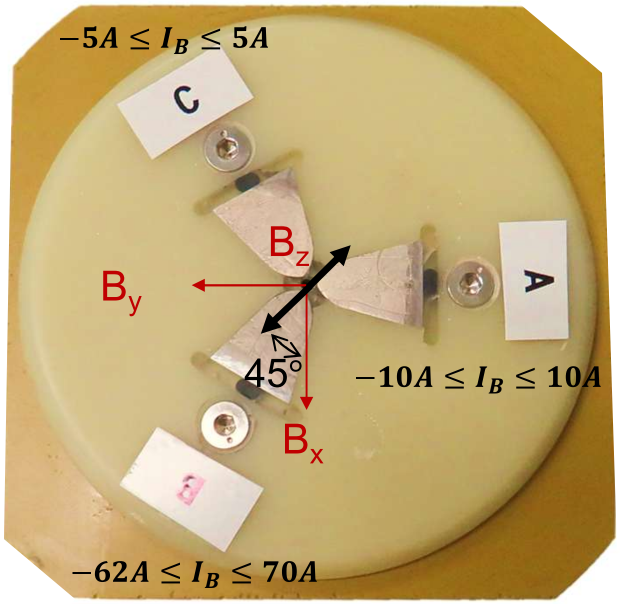
Working height of peak vertical field (5A – 45A)



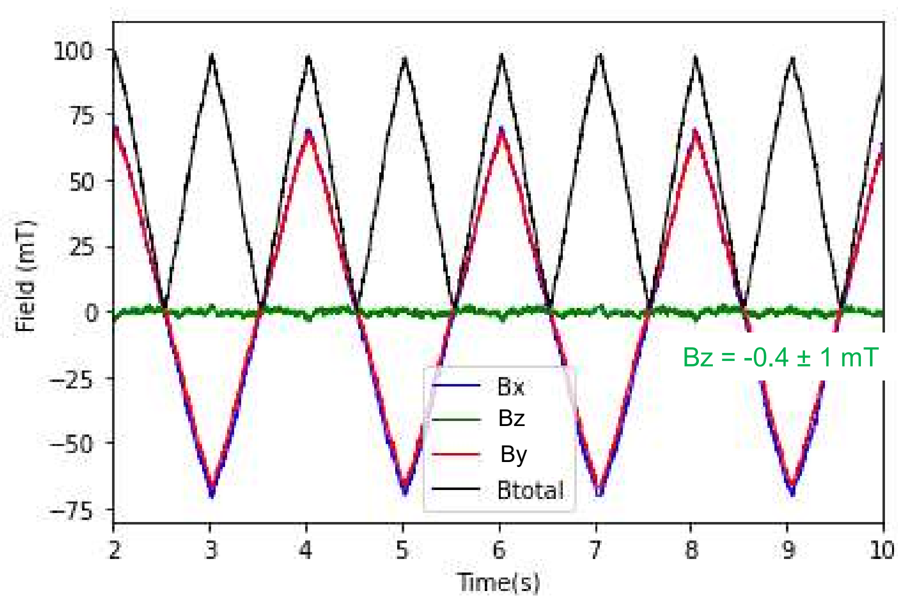
Projected vector field at a point (5204)

Generating triangular In-line vector field

100mT peak triangular waveform at 45º
5mm height



Measured 3-axis field

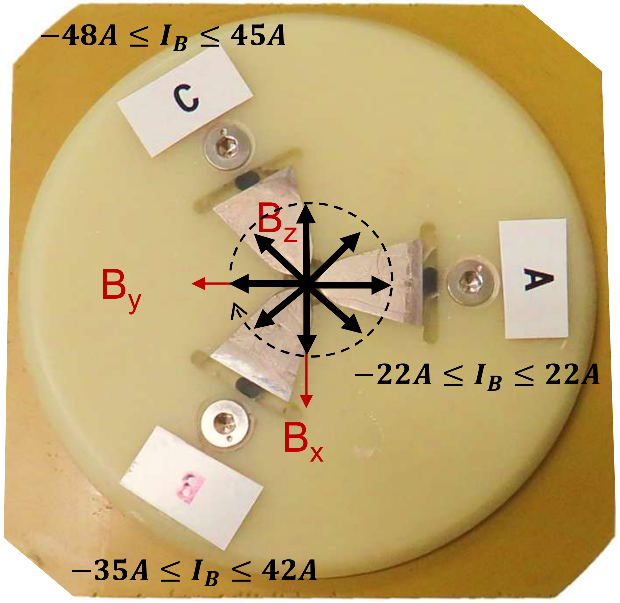


GMW Associates

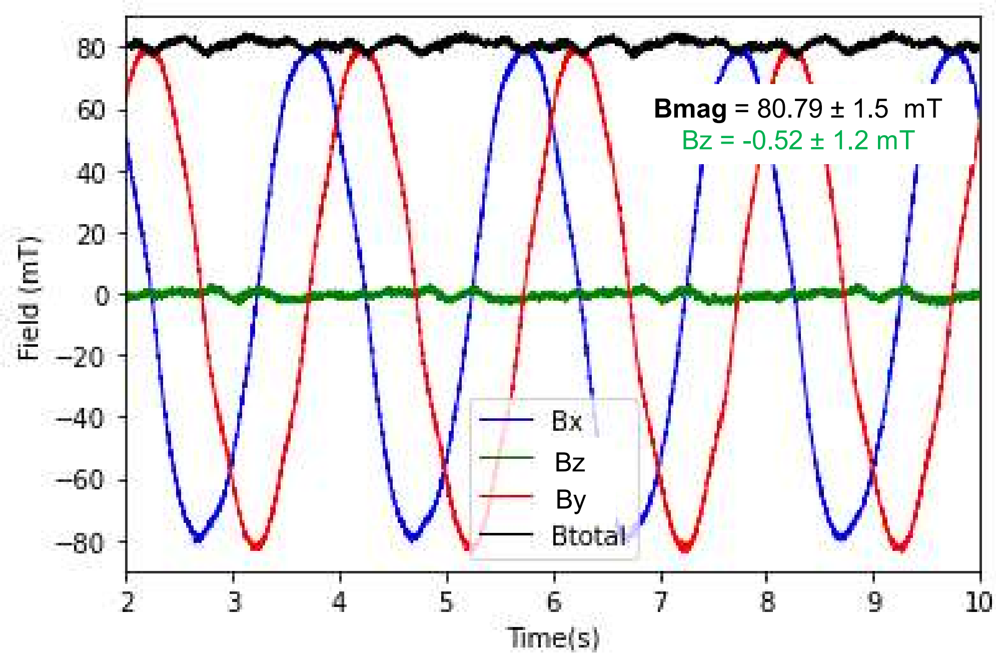
Projected vector field at a point (5204)

Generating In-plane rotational field

80mT continuous in-plane rotating field at 5mm height



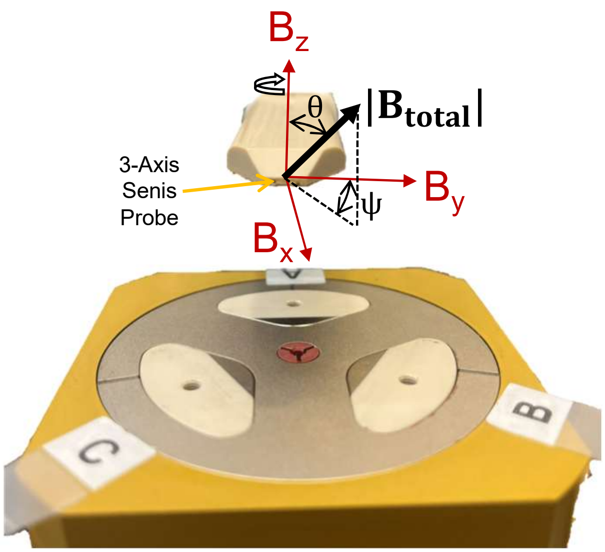
Measured 3-axis field



Projected Vector Field at a point (5204)

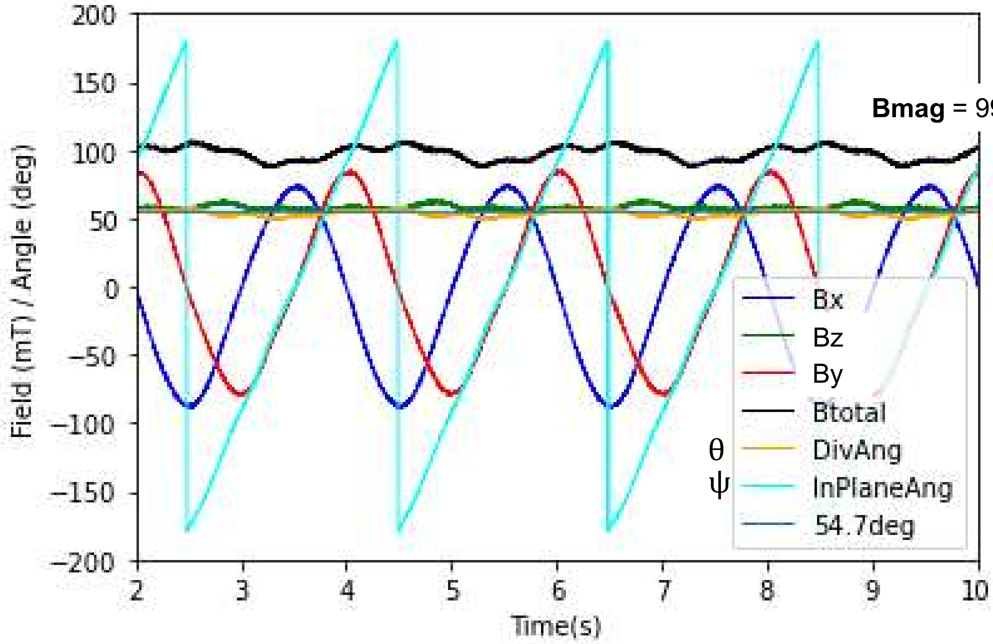
Generating conical rotating field

Continuous Rotating Azimuthal Angle ($-180° \leq \psi \leq 180°$) & Vertical offset angle $\theta \cong 54.7°$



5204 viewed without fluxplate
Field measured with fluxplate at 5mm height

Measured 3-axis field

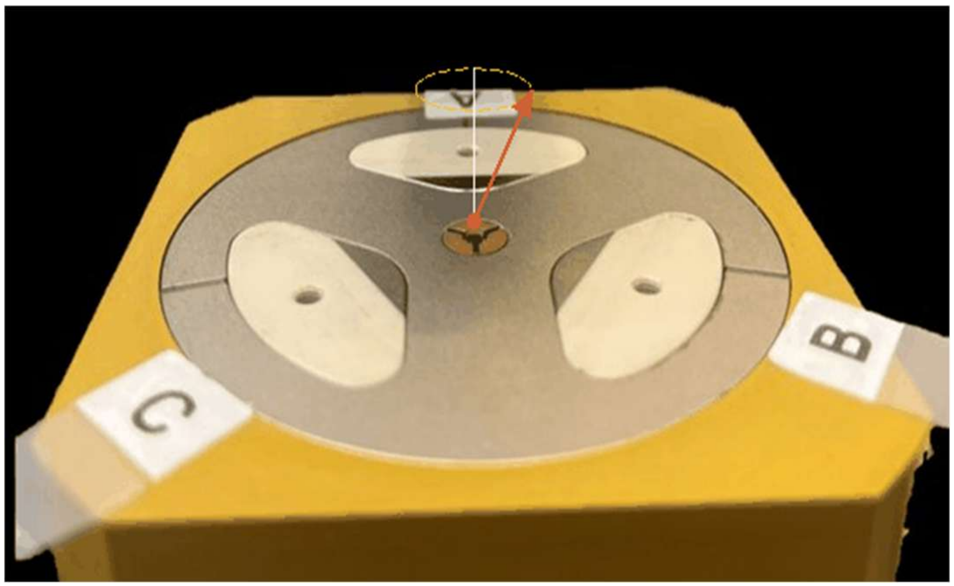


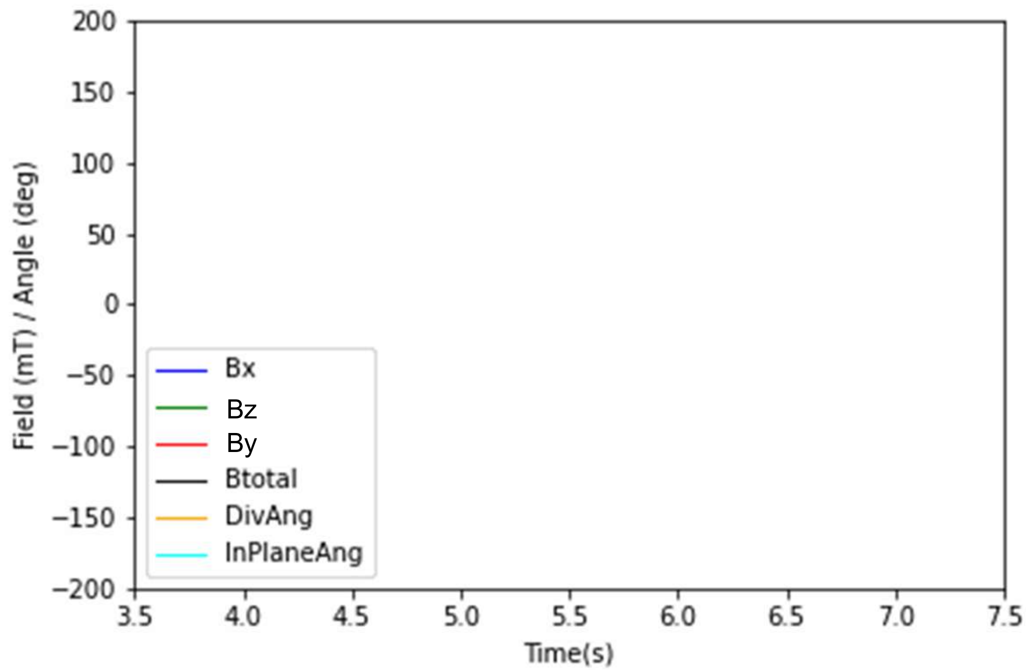
Bmag = 99.1 ± 4.1 mT

GMW Associates

Projected vector field at a point (5204)

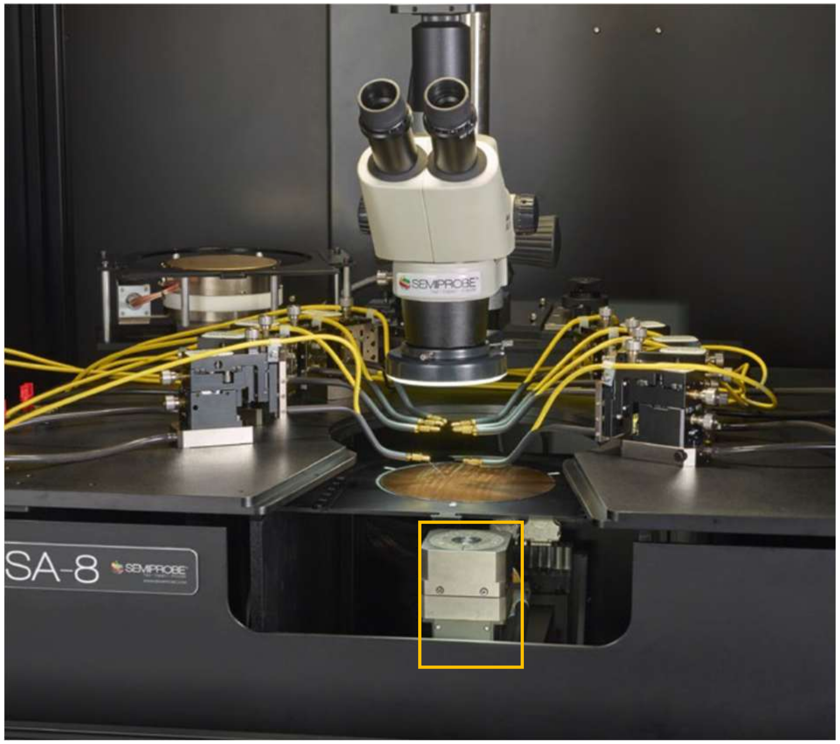
Generating conical rotating field (Animated based on actual measurement)





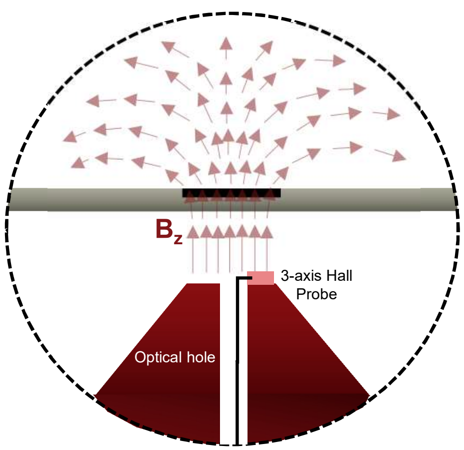
Magnet system

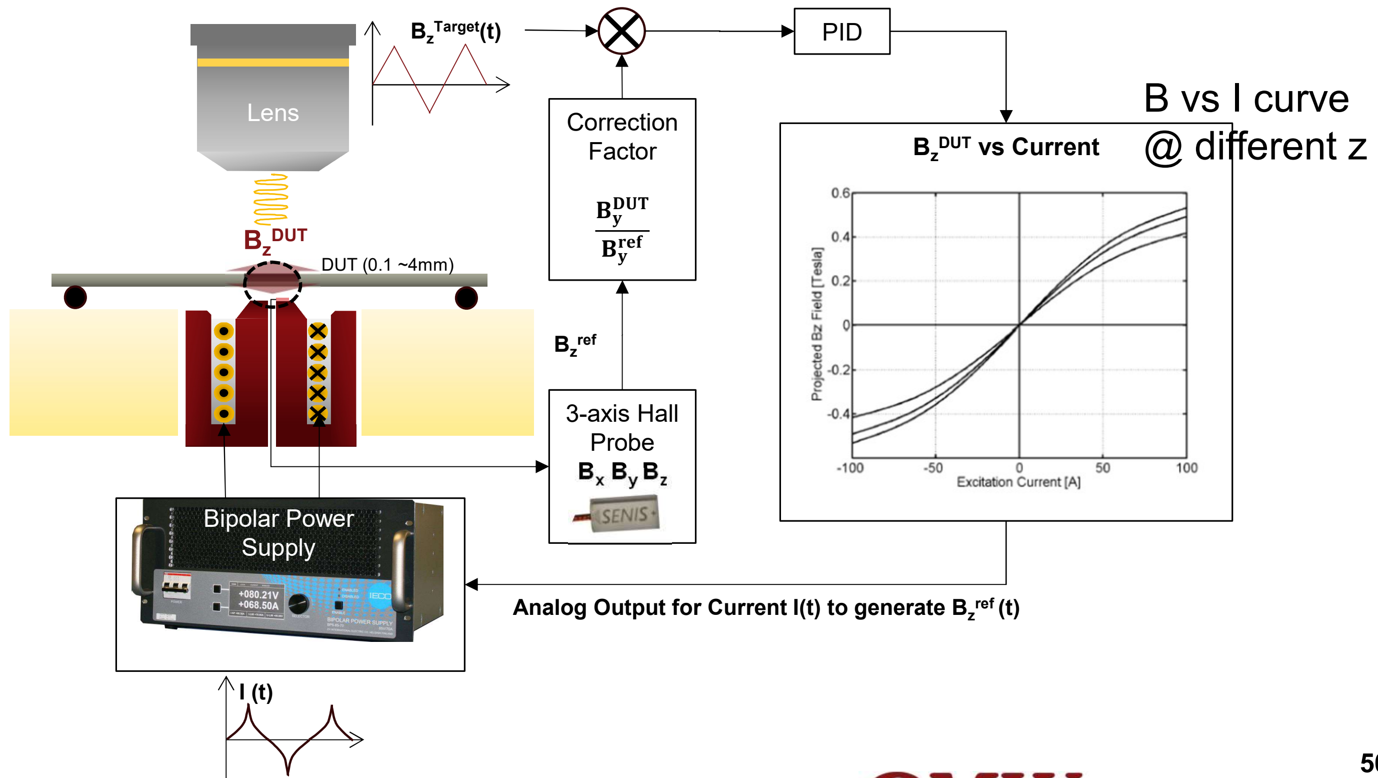
Magnet system example
5972 + BPS40-100 + 5203



Projected field magnet system overview

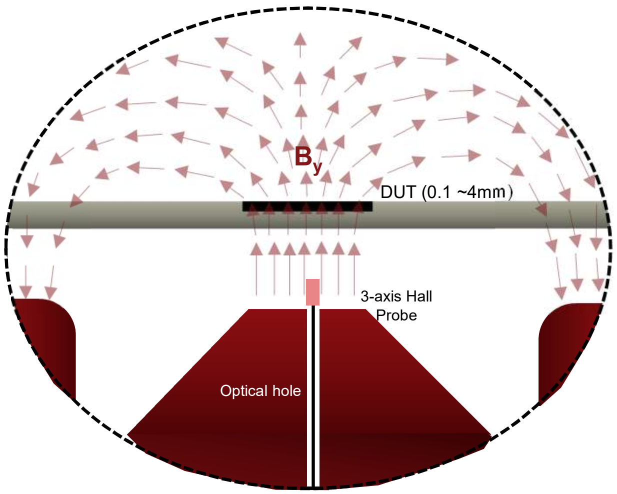
Close-loop field control (dynamic or DC)



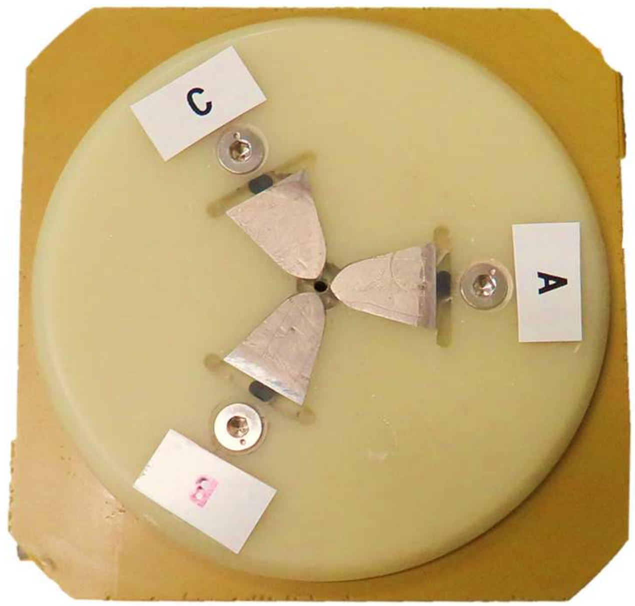


Axial hole on pole – Hall probe access?

Axial hole (2mm) for 3-axis probe access example

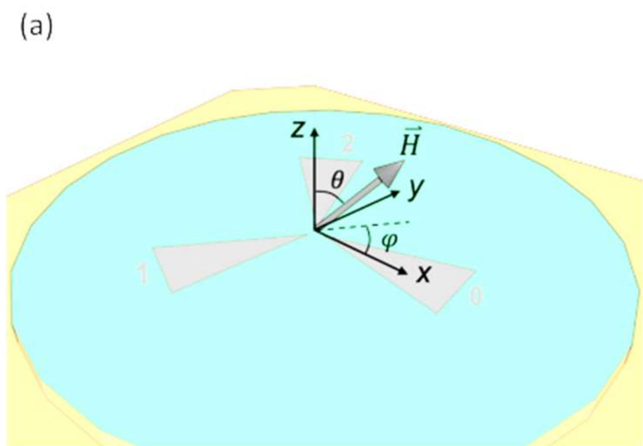


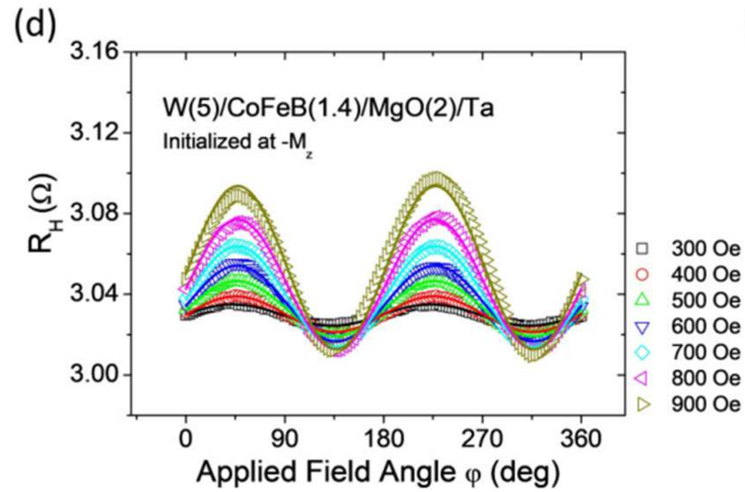
Only an Illustration



Applications of projected field electromagnet

Spin-orbit torque characterization with vector projected field magnet



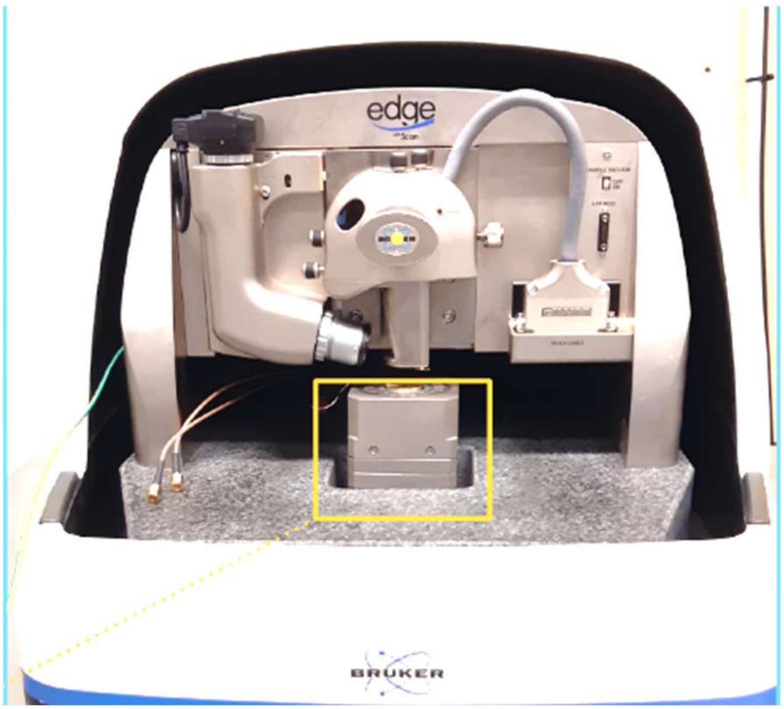


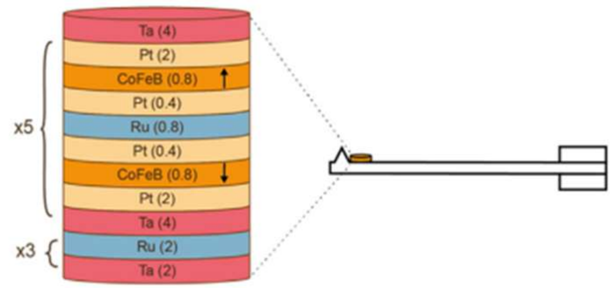
Planar Hall resistance function of applied field angle from 30 to 90mT

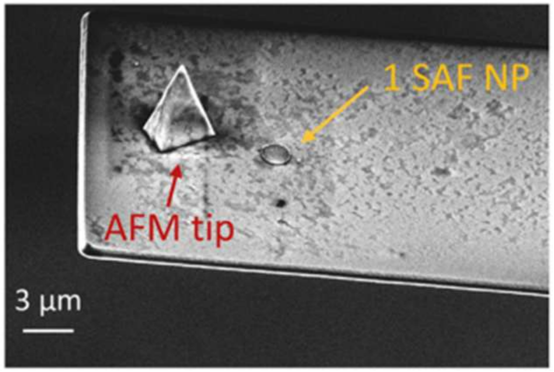
Huang Chao-Chung, et al., (2022), Phy. Review Research, 4, 033040.

Applications of projected field electromagnet

AFM cantilever magnetometry with Vertical Projected field Magnet



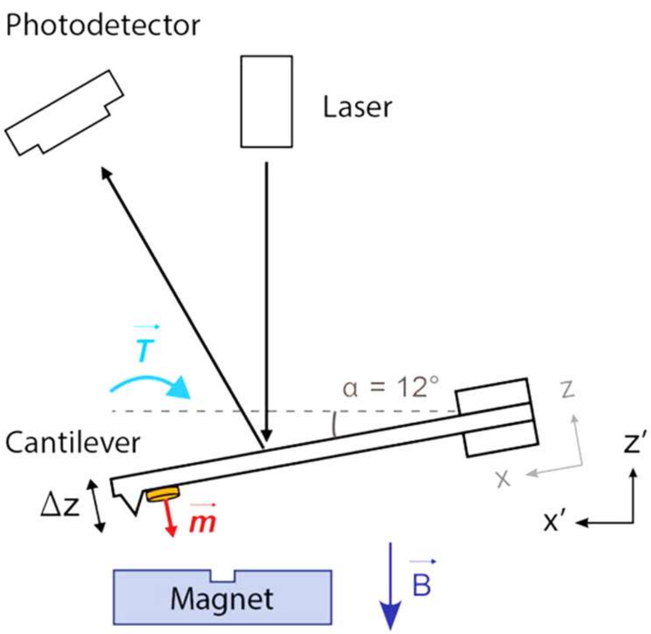


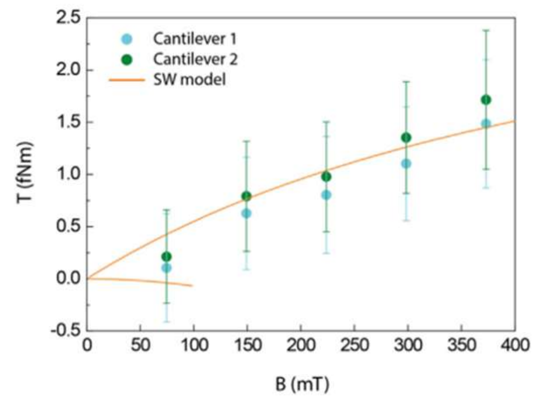


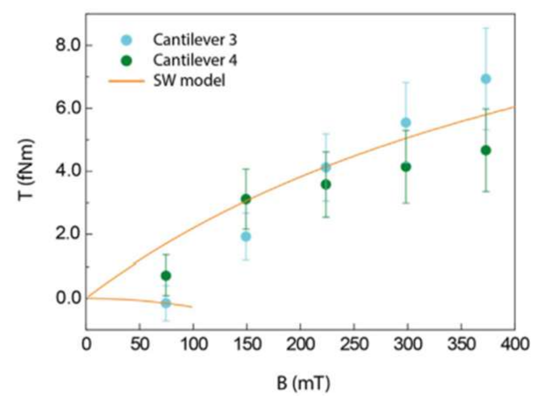
Efremova et al.,Appl. Phys. Lett. 126, 092406 (2025)

Applications of projected field electromagnet

Cantilever deflection (Torque) vs applied vertical field (B)







Efremova et al.,Appl. Phys. Lett. 126, 092406 (2025)

Applications of projected field electromagnet

Measuring single-cell kinetics under applied magnetic field

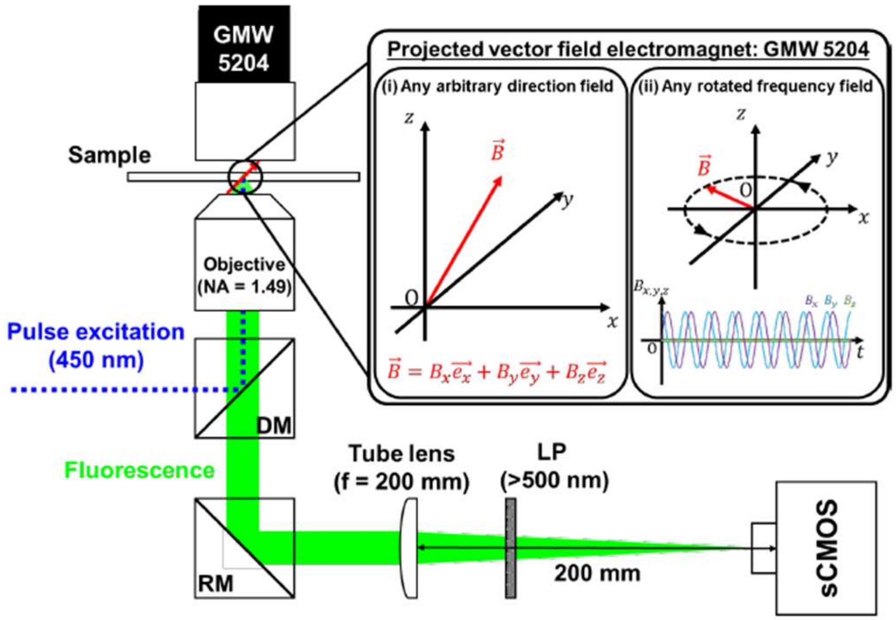
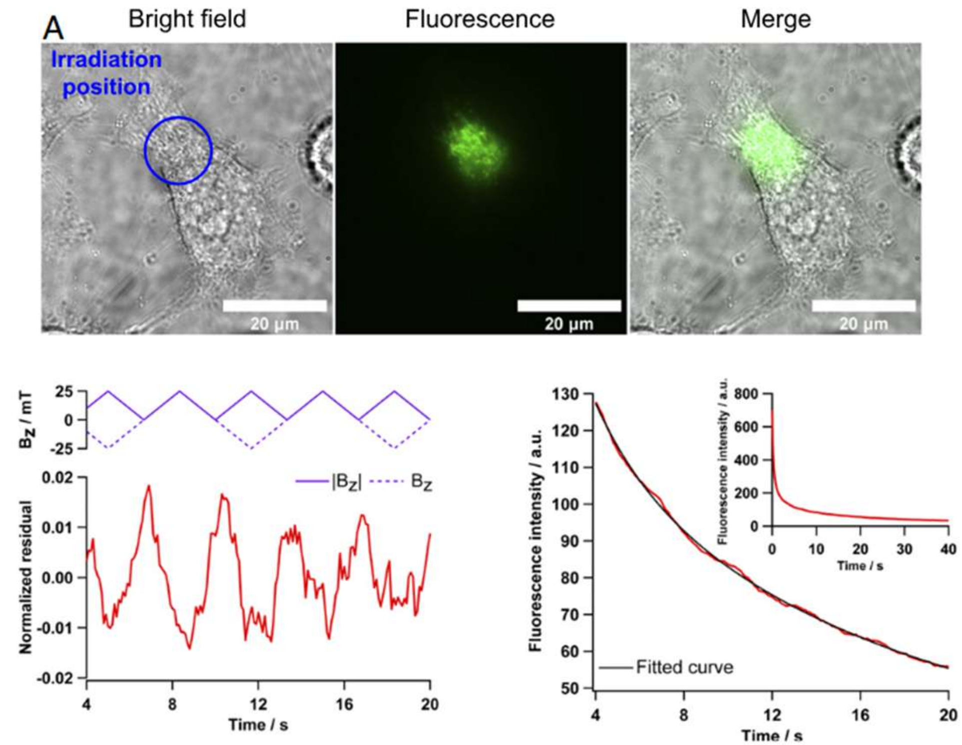


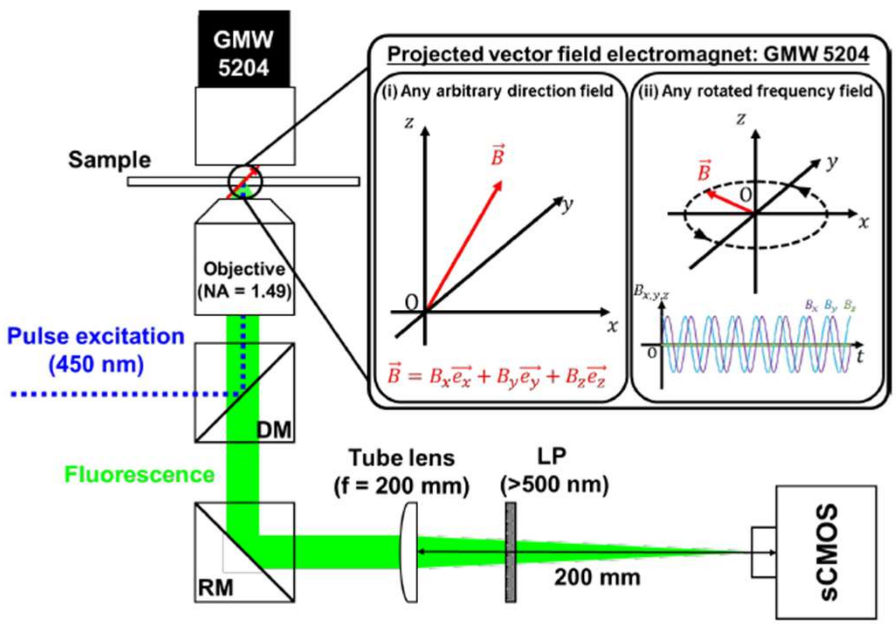
Fig. S4. Arrangement of the fluorescence microscope. The GMW5204 projected vector field electromagnet provides a magnetic field along any direction of up to 40 mT at the sample. DM = Dichroic mirror, RM = Reflection mirror, LP = Longpass filter.



Ikeya N., Woodward J.R., PNAS, 118(3) e2018043118 (2020).

Applications of projected field electromagnet

Cellular interaction with dynamic magnetic field vector



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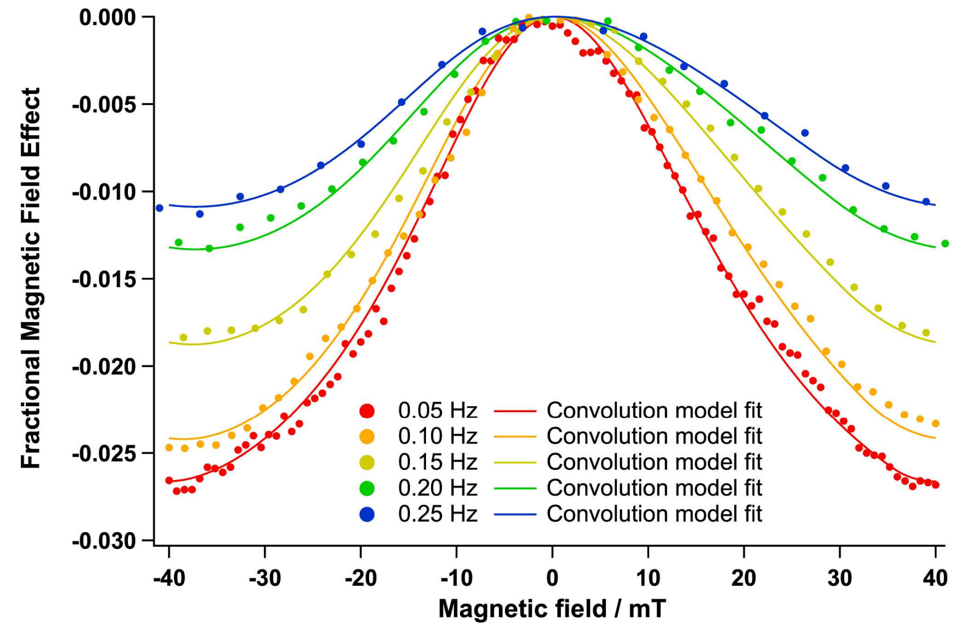

Ikeya N., Woodward J.R., PNAS, 118(3) e2018043118 (2020).

Thank You!

Ian Walker

Ian@gmw.com

Tom King

tom@gmw.com

Cerwyn Chiew

cerwyn@gmw.com

Yuqiang Qin

@gmw.com