# Shielding Setup for JPA Operation in the TASEH Detection Chain

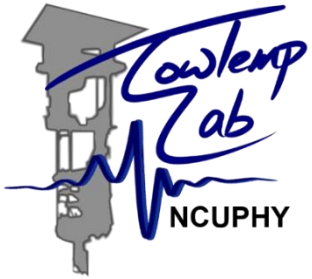
洪偉晟 **(Wei-Cheng Hung), TASEH Collaboration**

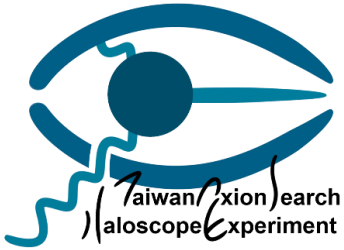
Advisor : 陳永富**(Yung-Fu Chen),** 張元翰**(Yuan-Hann Chang)**

JPAs team ,Low Temperature Physics Lab, NCU

Taiwan Axion Search Experiment with Haloscope, NCU






# Axion detection sensitivity

Cavity & Magnet

$$SNR = \frac{P_a}{\sigma}$$

JPA & data taking strategy

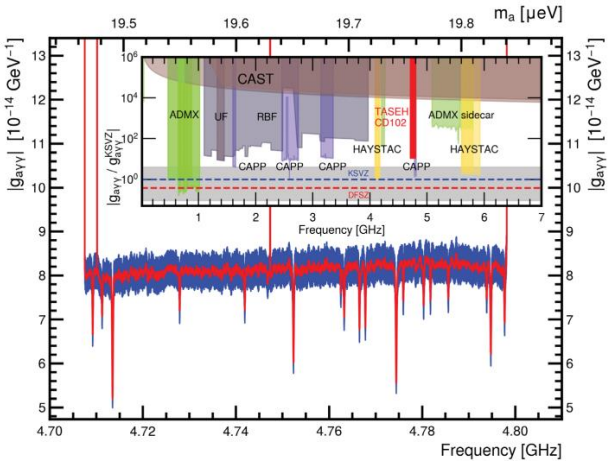
$$P_a = \left(g_{a\gamma\gamma}^2 \frac{\hbar^3 c^3 \rho_a}{m_a^2}\right) \times \left(\omega_c \frac{1}{\mu_0} B_0^2 V C Q_L \frac{\beta}{1+\beta}\right)$$

$$\sigma = \frac{k_B T_{sys} \Delta f}{SSE\sqrt{N}}$$

| parameter | Remarks |
|---|---|
| $SNR$ | Signal to noise ratio |
| $P_a$ | Typical axion signal power |
| $\sigma$ | Average noise power |
| $T_{sys}$ | Effective system noise temperature |
| $\Delta f$ | Resolution bin width |
| $N_{a102}$ | Amount of data |
| SSE | Scan |

The efficiency of reducing "$\sigma$"

1. $T_{sys}$ factor of 1
2. $N$: factor of square root




From TASEH CD102 result :

① $P_a \sim 1.4 \times 10^{-24} W$

② $\boldsymbol{T_{sys} \sim 2K}, \rightarrow \sigma \sim 1.4 \times 10^{-23} W$

$\rightarrow \sim 8.1 g_{a\gamma\gamma}$

After integrating JPA in detection chain

① $P_a \sim 1.4 \times 10^{-24} W$

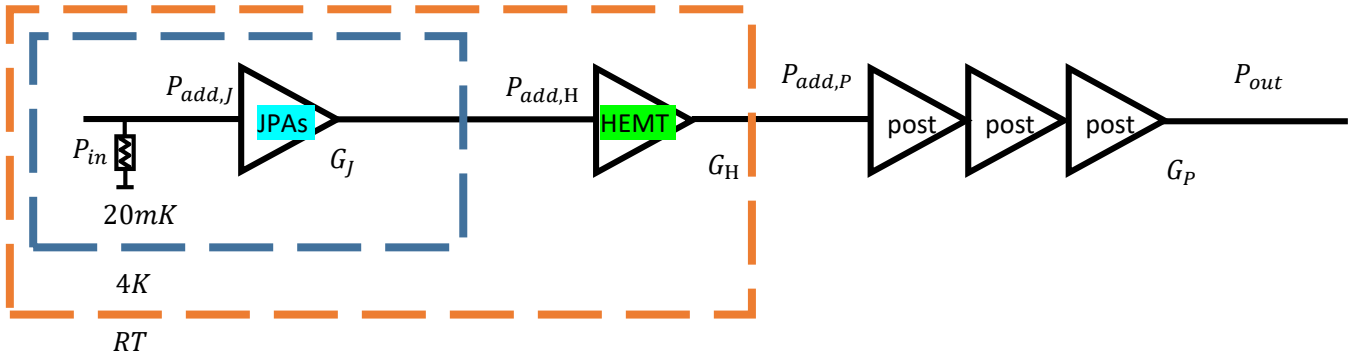
② $\boldsymbol{T_{sys} \sim 0.3K}, \rightarrow \sigma \sim 2.1 \times 10^{-24} W$

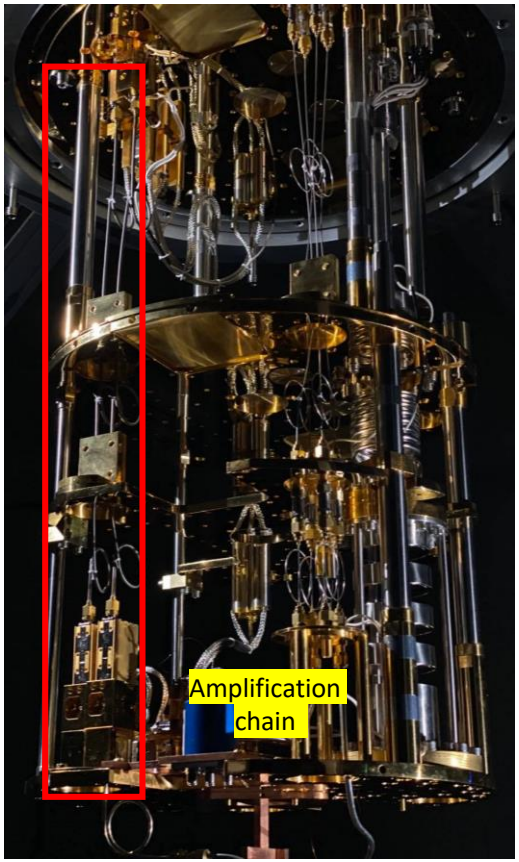
$\rightarrow \sim 3.13 g_{a\gamma\gamma}$ (with the same data taking time)



Hsin Chang et al, Phys. Rev. Lett. 129, 111802 (2022)

# Amplification chain




Noise power after sequential Amplifiers:

$$P_{out} = G_p(G_H(G_J(P_{vc} + P_{add,J}) + P_{add,H}) + P_{add,P})$$

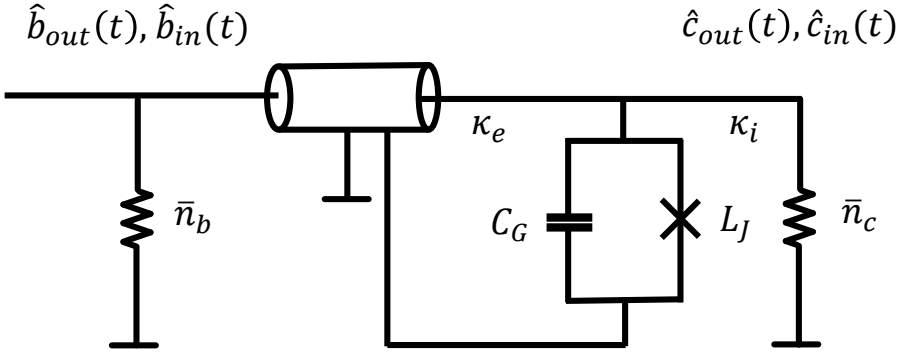
$$P_{out} = G_p G_H G_J \left( \left( (P_{in} + P_{add,J}) + \frac{P_{add,H}}{G_J} \right) + \frac{P_{add,P}}{G_J G_H} \right)$$

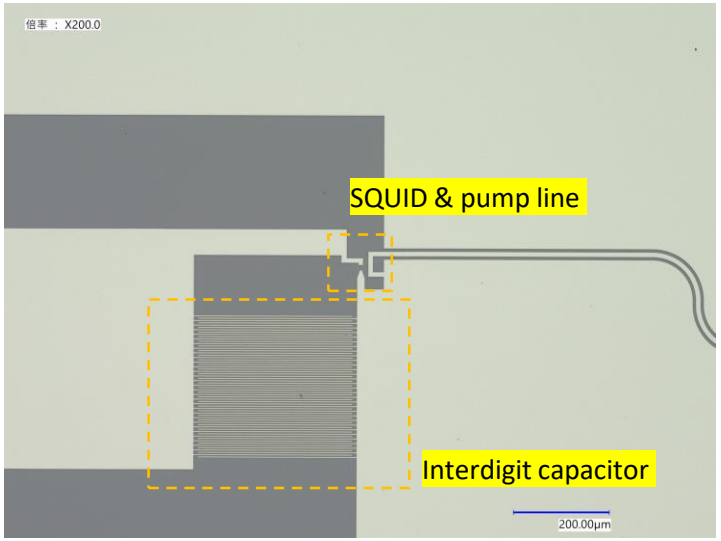
$$P_{out} = G_{tot} k_B T_{sys} \Delta f = G_p G_H G_J \Delta f (\mathrm{T_{in}} + \mathrm{T_{add,J}} + \frac{\mathrm{T_{add,H}}}{G_J} + \frac{\mathrm{T_{add,P}}}{G_J G_H})$$

$$T_{sys} = \mathrm{T_{in}} + \mathrm{T_{add,J}} + \frac{\mathrm{T_{add,H}}}{G_J} + \frac{\mathrm{T_{add,P}}}{G_J G_H}$$

| parameter | Remarks |
|---|---|
| $G$ | Gain from amplifier |
| $P_{add}$ | Add noise from amplifier |
| $T$ | Effective noise temperature |

# Josephson parametric amplifier



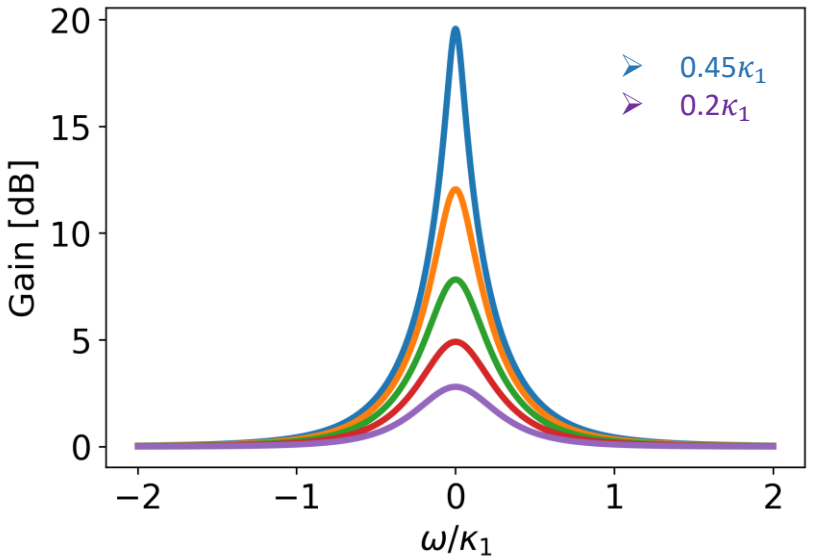

$$\hat{H} = \frac{1}{C_G}\hat{q}^2 + \frac{\hbar}{2e}I_c(1-\cos\hat{\delta})$$

$$\hat{H}_{JPA} = \hbar\omega_r\hat{a}^\dagger\hat{a} + i\hbar\eta\left(e^{i\phi}\hat{a}^\dagger\hat{a}^\dagger - e^{-i\phi}\hat{a}\hat{a}\right)$$

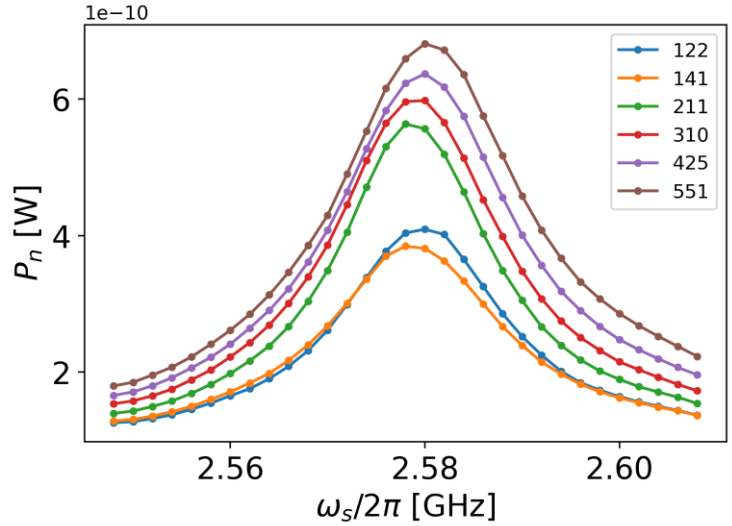
$$\dot{\hat{a}} = \frac{i}{\hbar}\left[\hat{H}_{JPA}, \hat{a}\right] - \frac{1}{2}\kappa\hat{a} + \sqrt{\kappa_e}\hat{b}_{in}(t) + \sqrt{\kappa_i}\hat{c}_{in}(t)$$

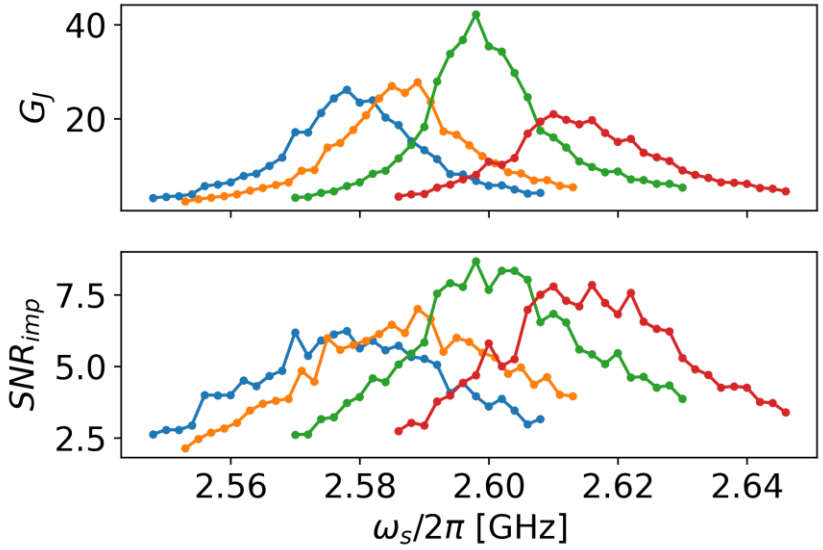
$$\hat{b}_{out} + \hat{b}_{in} = \sqrt{\kappa_e}\hat{a}$$

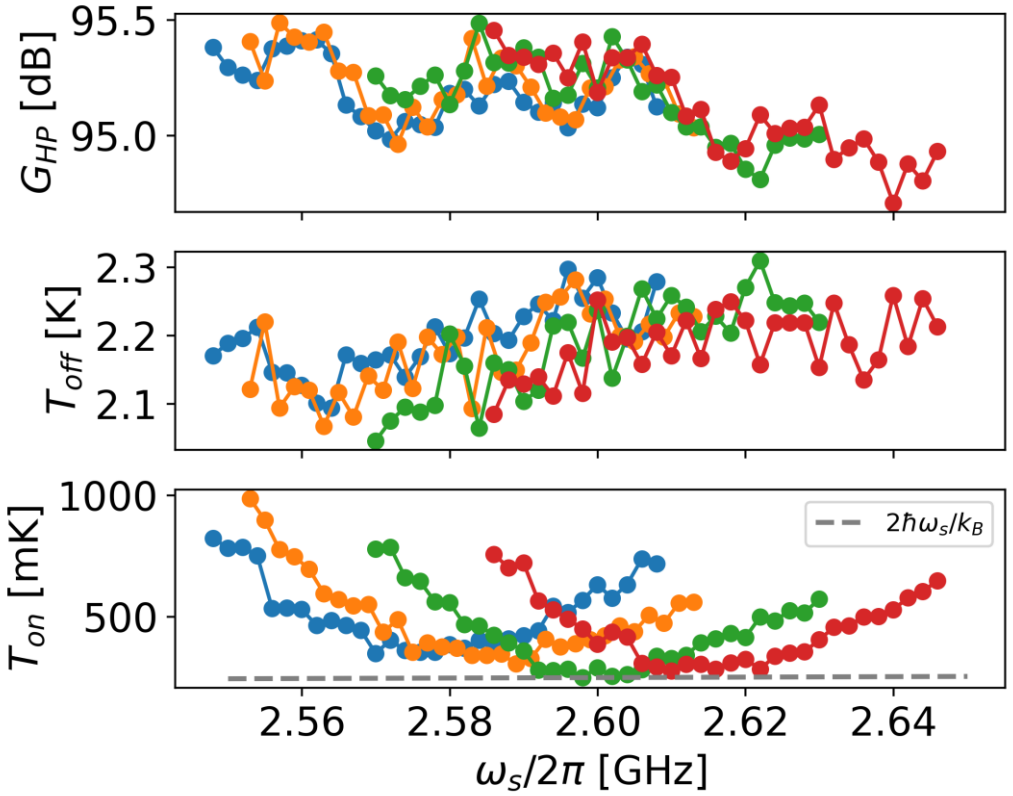
$$\mathrm{G}_s(0) = \left|-1 + \kappa_1 \frac{\left(-i(\omega+\widetilde{\omega_s}) + \frac{\kappa}{2}\right)}{\left(-\omega^2 + \widetilde{\omega_s}^2\right) + \frac{1}{4}\kappa^2 - i\omega\kappa - \lambda^2}\right|^2$$



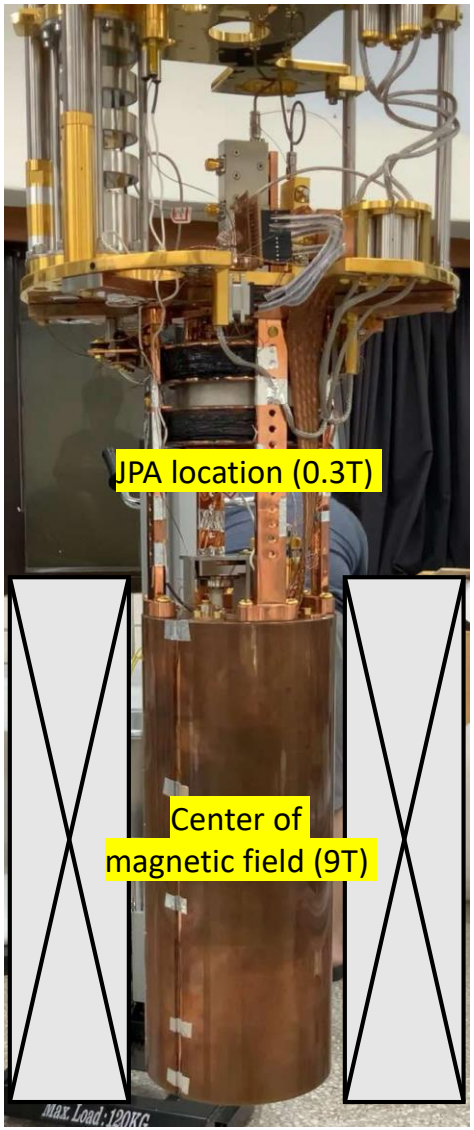
# Gain and noise



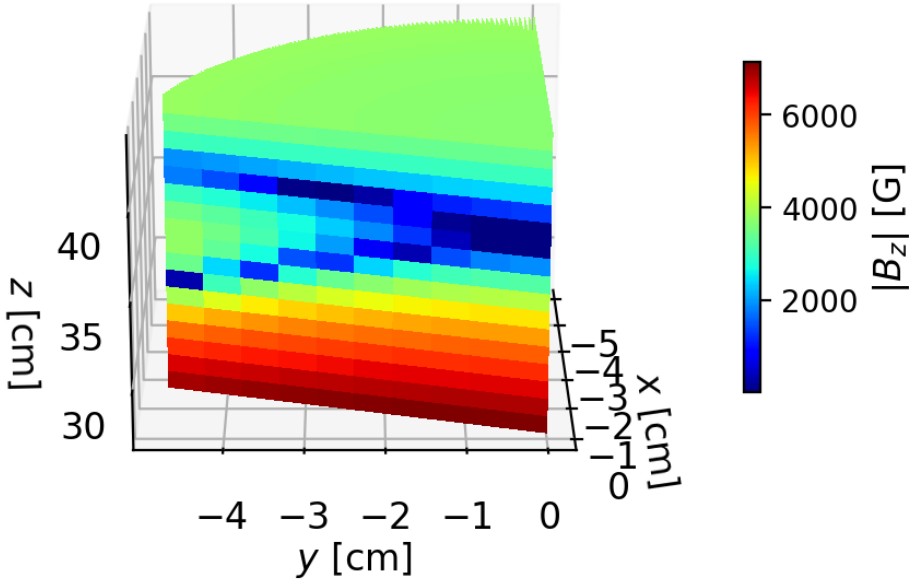



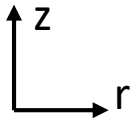
# The challenges




Center of the MX plate (z =40, r=0)



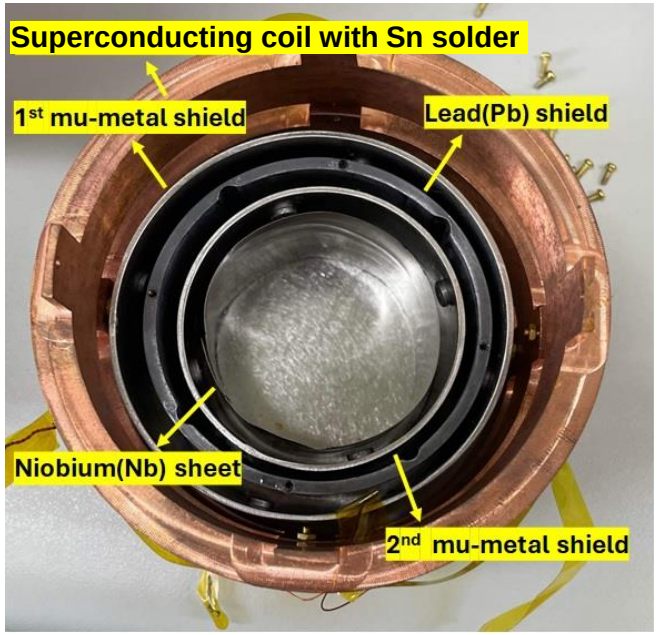

Center of the cavity (z =0, r=0)



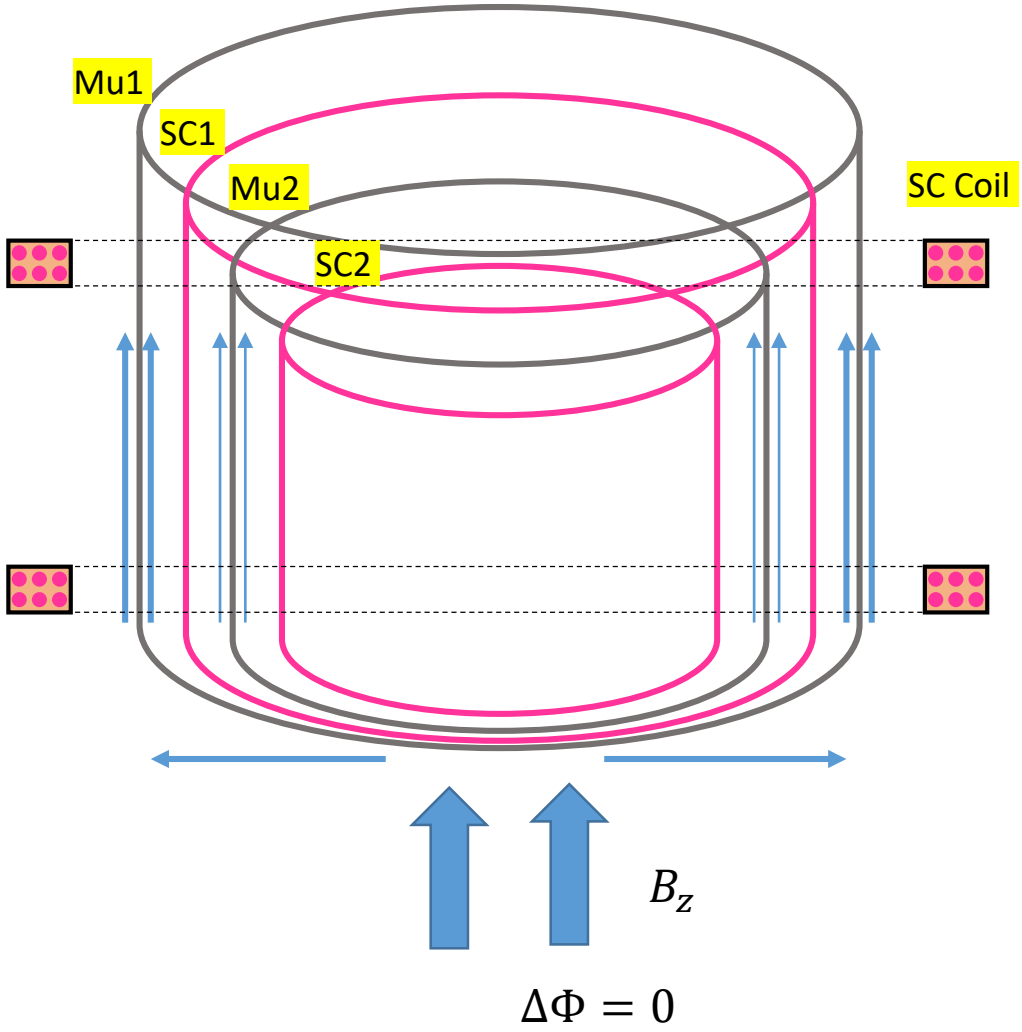

| | r =0 cm | r=2 cm |
|---|---|---|
| 36cm | 56G<br>0G | 20G<br>80G |
| 32cm | 1330G<br>0G | 1125G<br>604G |
| 29cm | 4109G<br>0G | 3866G<br>1257G |

# HATSTAC style shielding

1. Compensate Coil (SC coil)
2. Mu-4K shield (Mu1)
3. Pb SC shield (SC1)
4. Mu-4K shield(Mu2)
5. Nb shield (SC2)



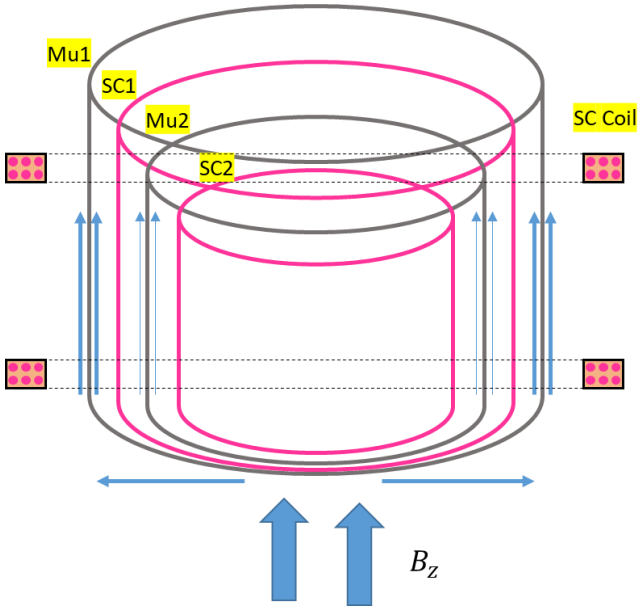

**Our 5-layer shielding**

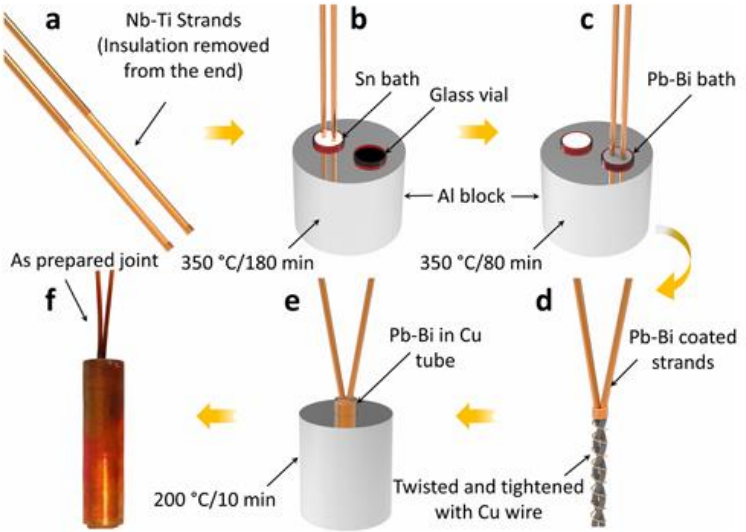





Shielding design concept follows HAYSTAC

# Shielding configuration

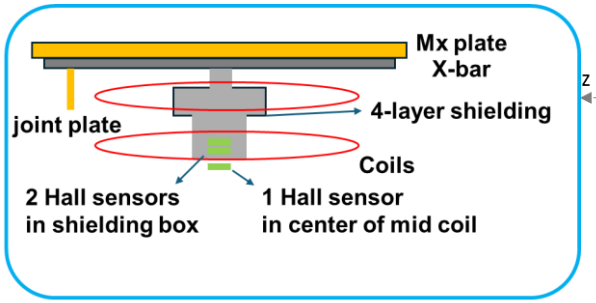



| | Material | Field constrain | Principle | Function |
|---|---|---|---|---|
| SC Coil | Nb-Ti filaments | 9T (critical field,Hc1) | Persistent current | Canceling |
| Mu1 | Mu-4K | 0.6T (saturation field) | ferromagnetism | Trapping |
| SC1 | Pb | 0.08T (critical field) | Meisner effect | Expelling |
| Mu2 | Mu-4K | 0.6T (saturation field) | ferromagnetism | Trapping |
| SC2 | Nb | 0.2T (critical field, Hc1) | Meisner effect | Expelling |

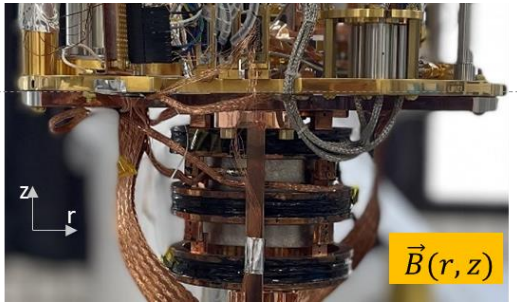
*Scientific Reports volume 9, Article number: 14287 (2019)*

# Leak field inside the shielding



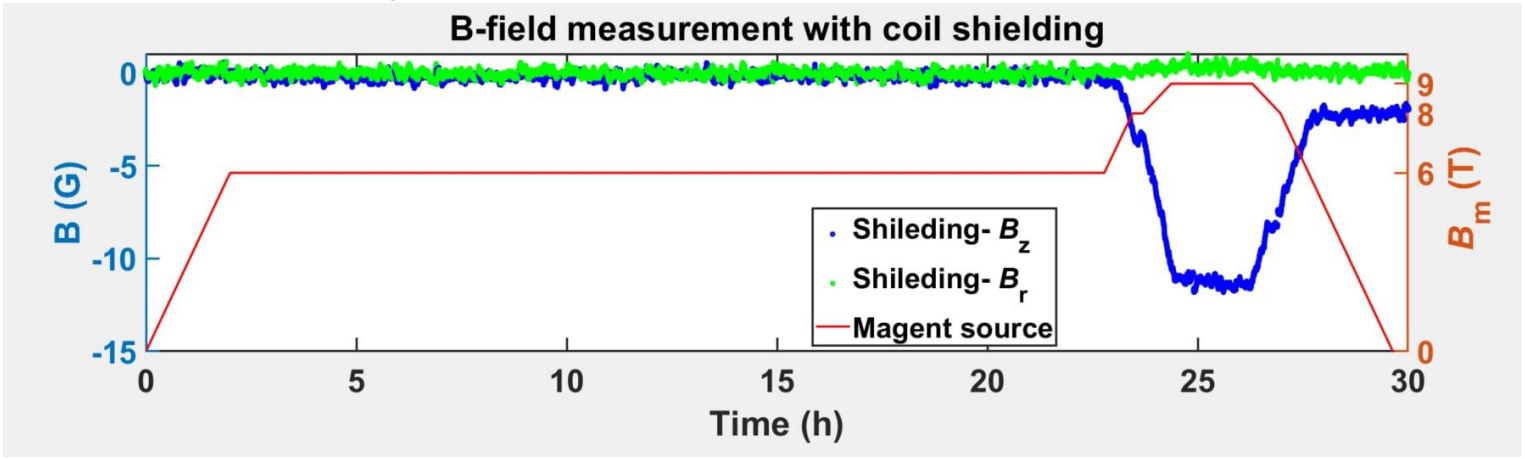

Schematic of setup

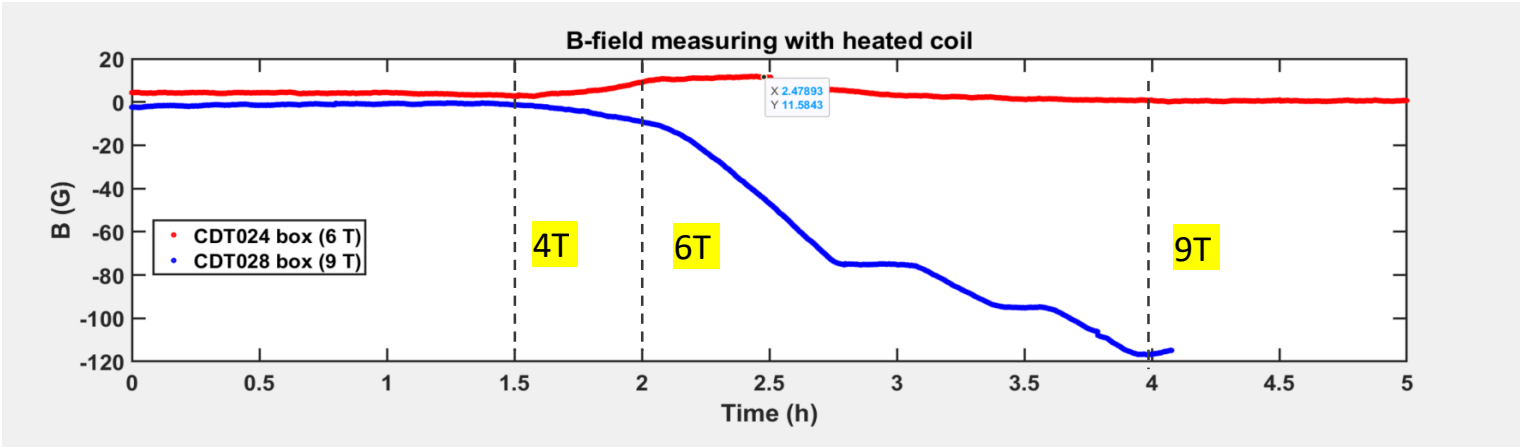
z =40cm



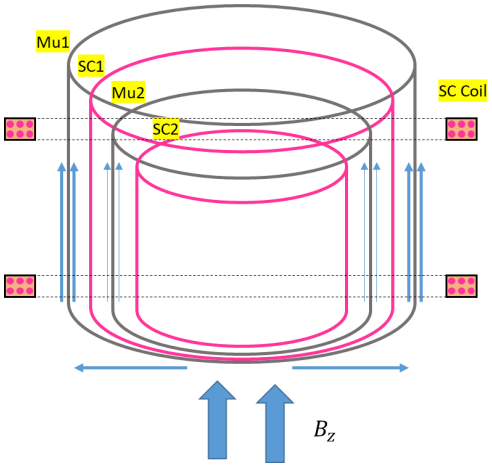

Hall sensor sensitivity ~1G

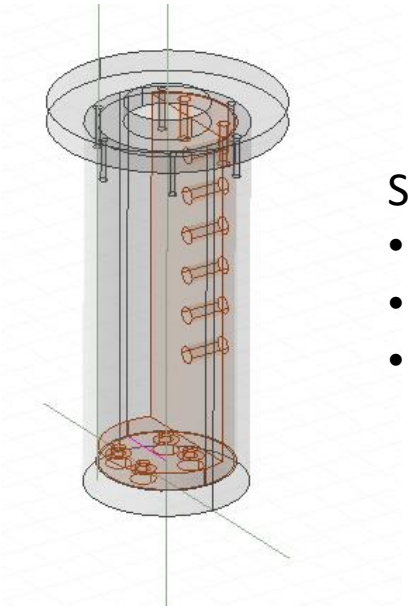
Shielding set survive ~6T



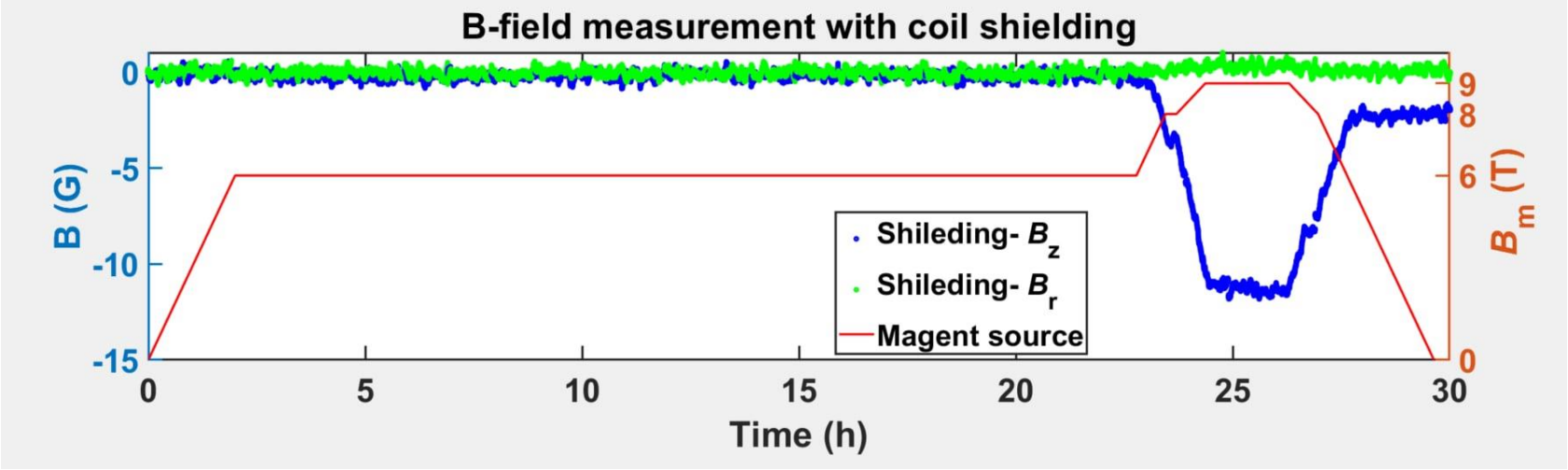
# New shielding design : SINA version



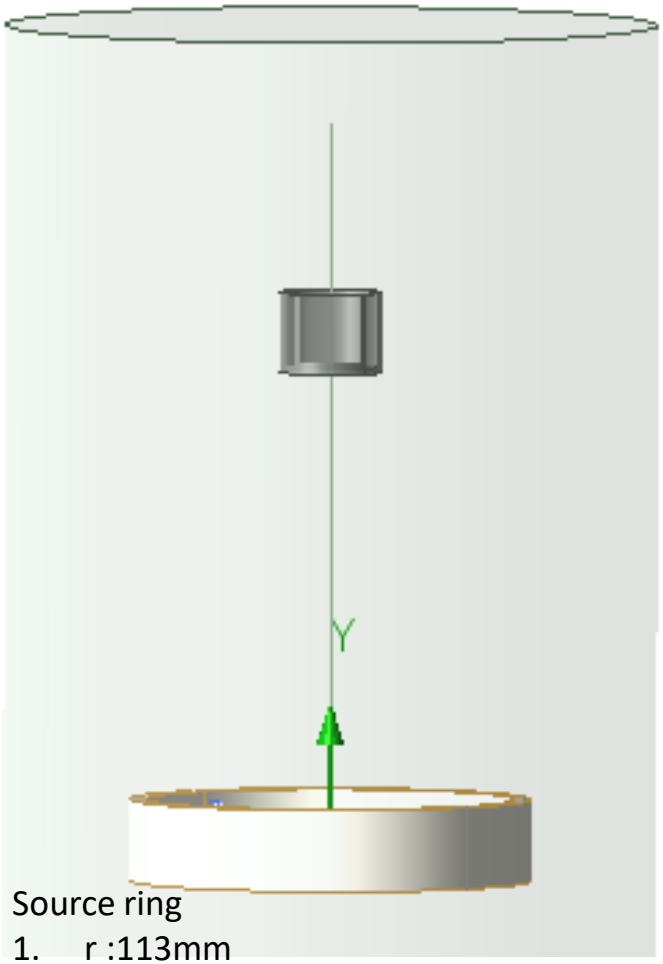



SINA shielding set :

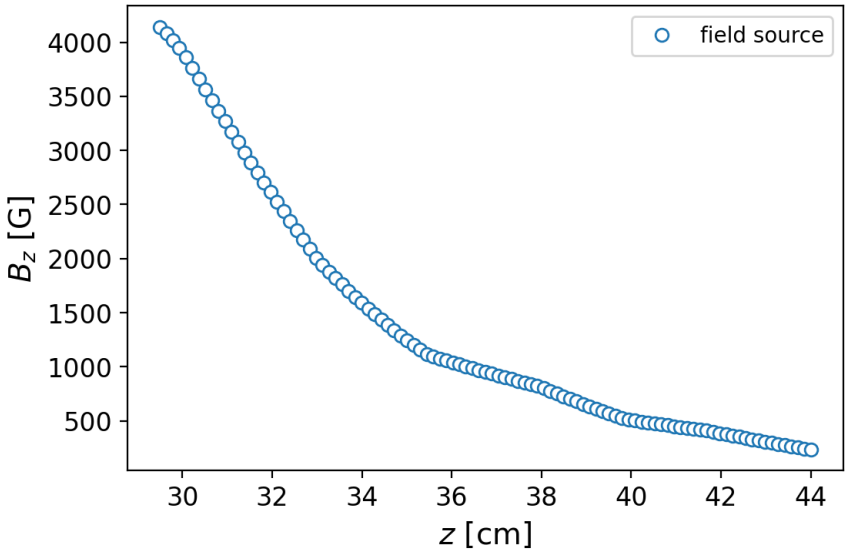
- Single layer metal shielding
- High field material
- Dual compensate coil

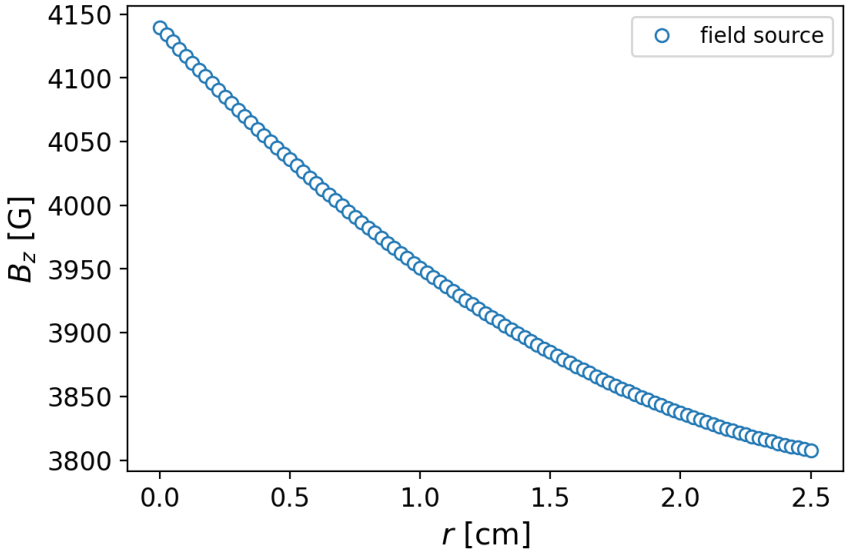


# Numerical study of the shielding effect

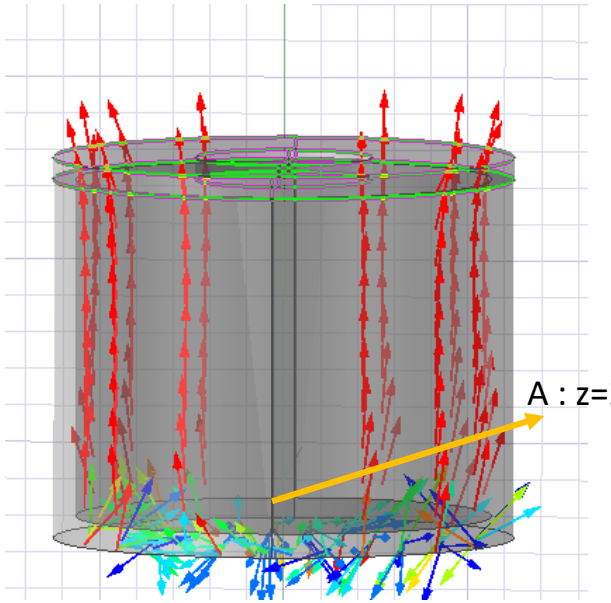


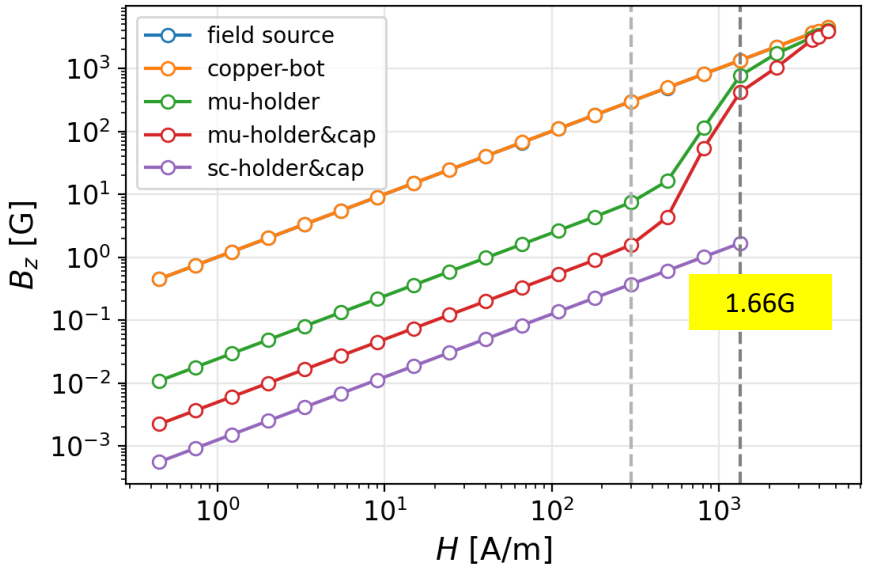
Source ring
1. r :113mm
2. Material :PEC
3. Bz (z=29.5,r =0) : 4100G

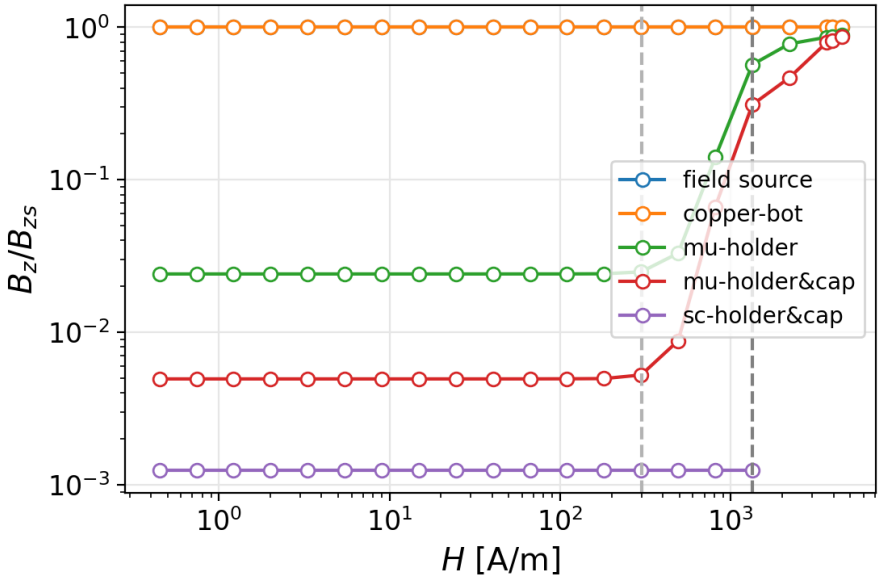


# B-H curve of HAYSTAC single layer shielding

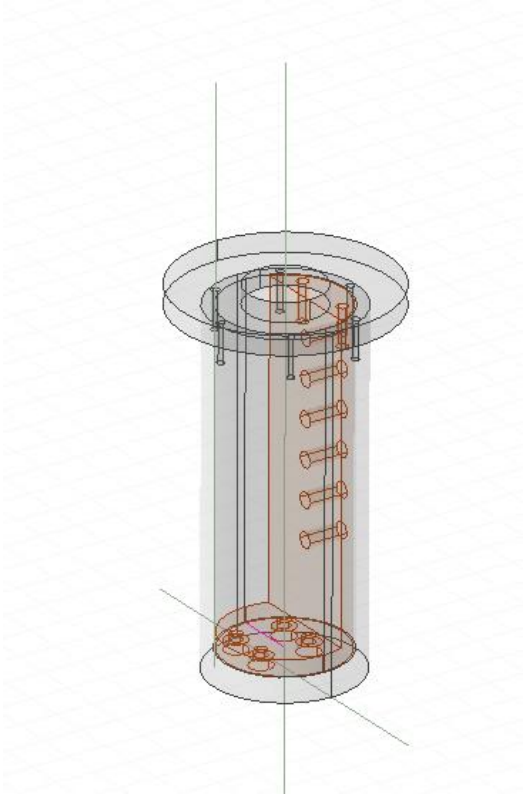


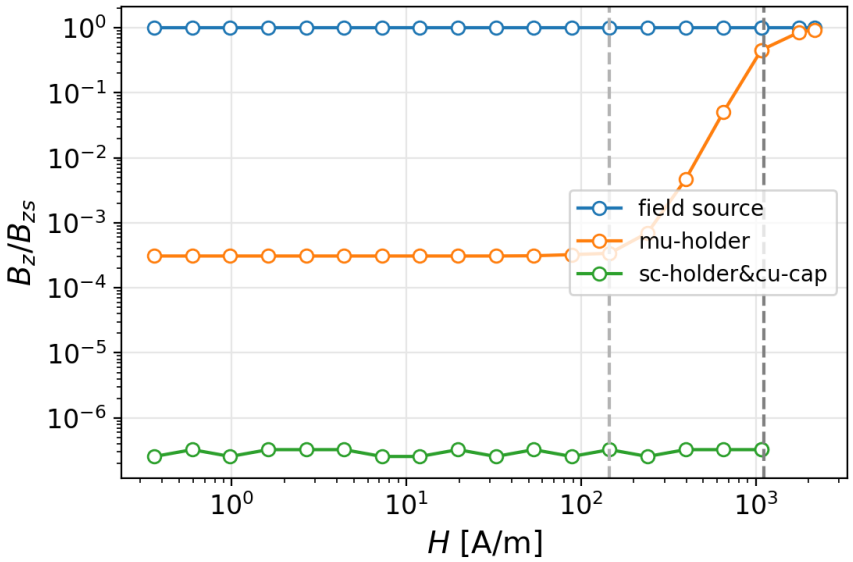



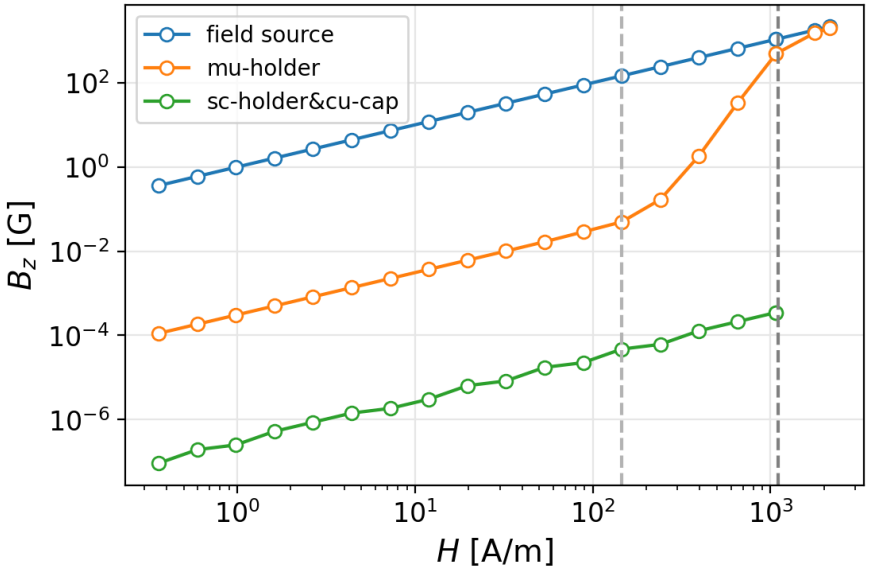




| Material | source | Mu bot | SC |
|---|---|---|---|
| Reduction factor | 1 | 3.9e-4 | 3.2e-7 |
| High field constrain (H) | -- | 300G | 1316G |

# B-H curve of SINA single layer shielding



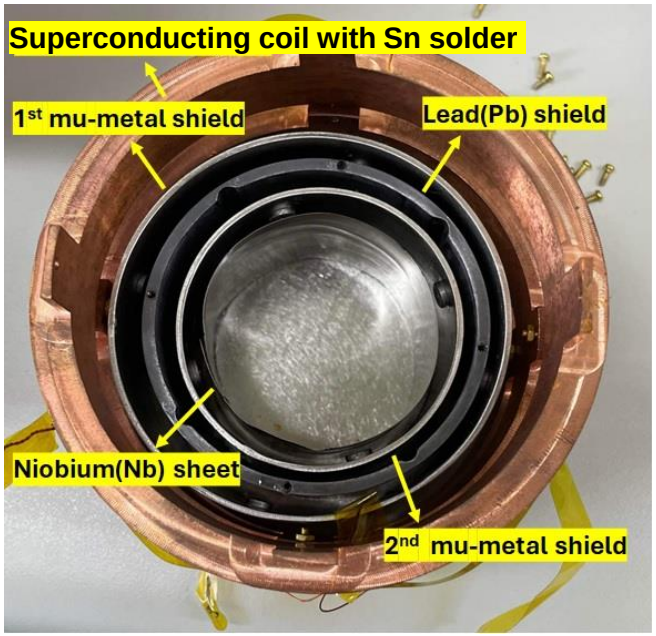



| Material | source | Mu bot | SC |
|---|---|---|---|
| Reduction factor | 1 | 3.9e-4 | 3.2e-7 |
| High field constrain (H) | -- | 145G | 1085G |

# Following plan

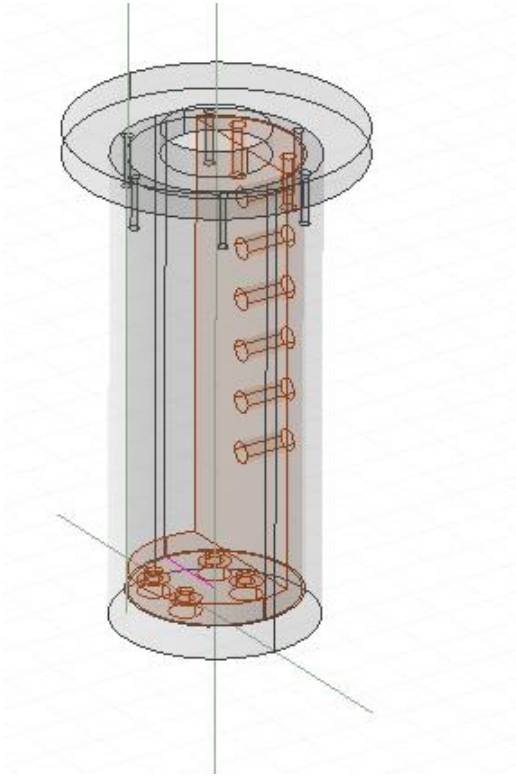
Short term




**Our 5-layer shielding**

Operating the JPA at 6T

Long term



Operating the JPA to 9T