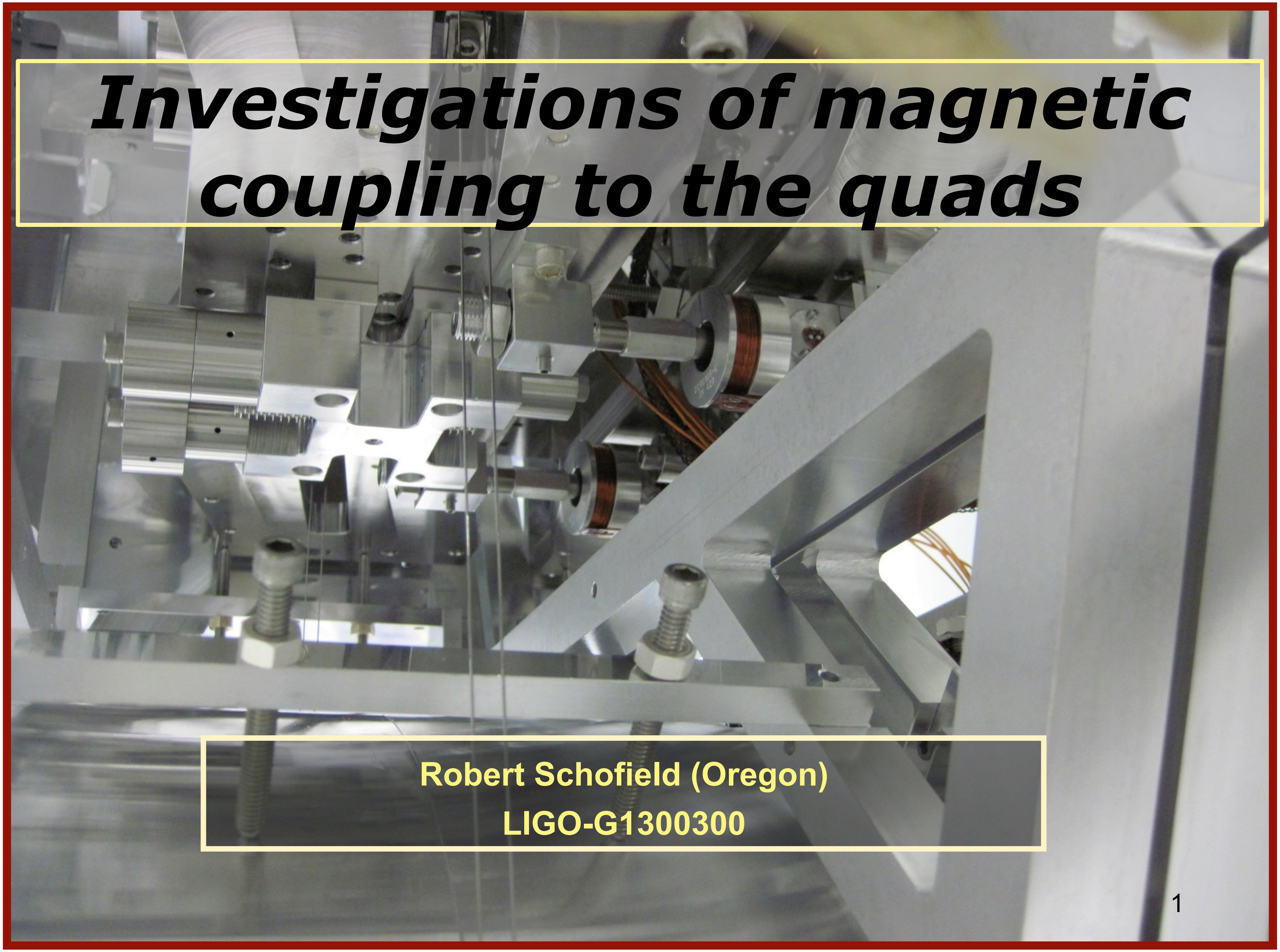
Investigations of magnetic coupling to the quads

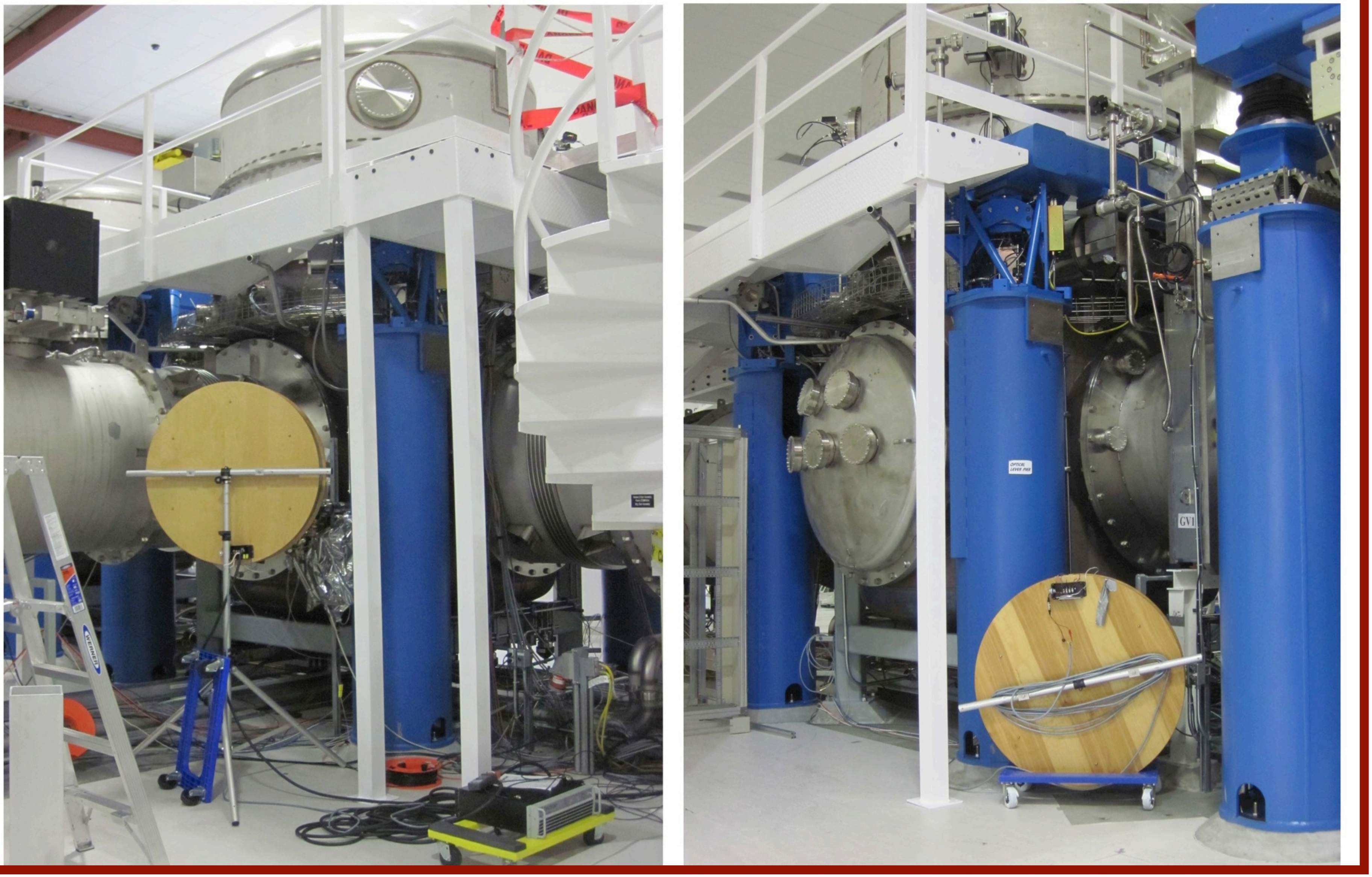


Robert Schofield (Oregon)

LIGO-G1300300

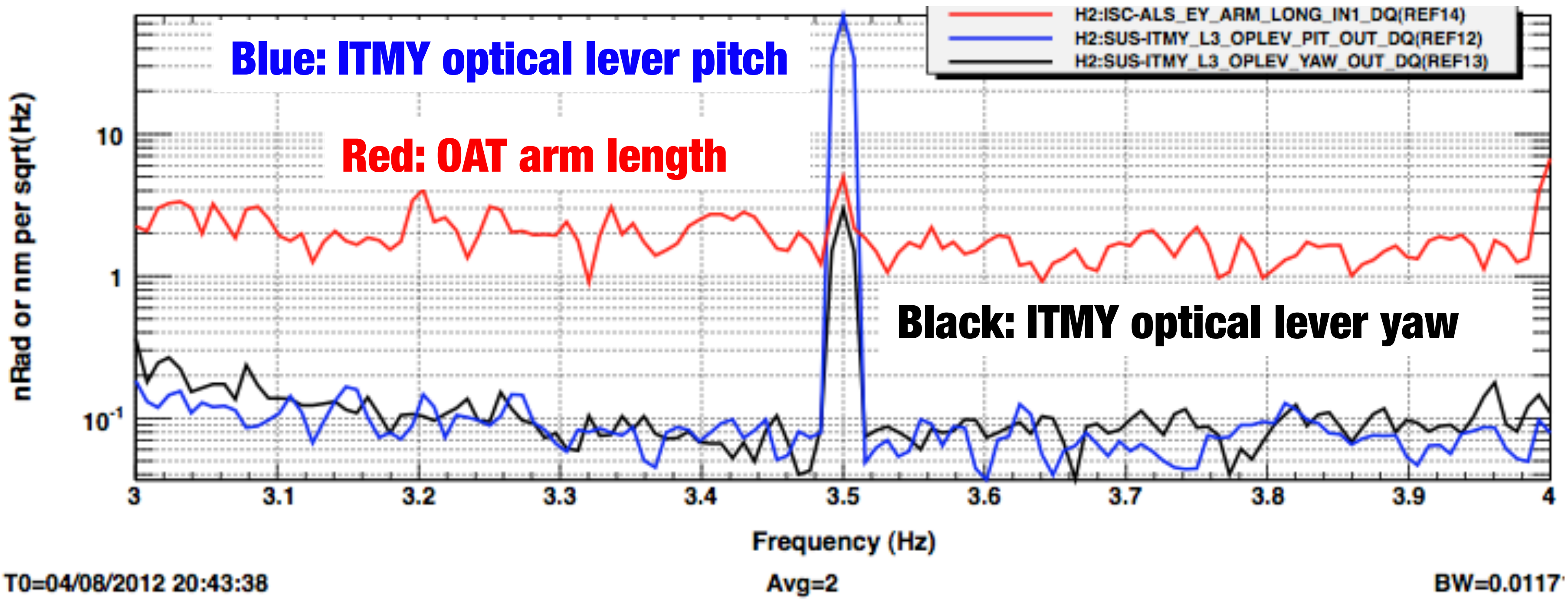
Excess magnetic coupling in OAT

Injection coils at ITMY in pseudo-Helmholtz configuration



3.5 Hz Injection

Evident in one arm test arm length and optical lever



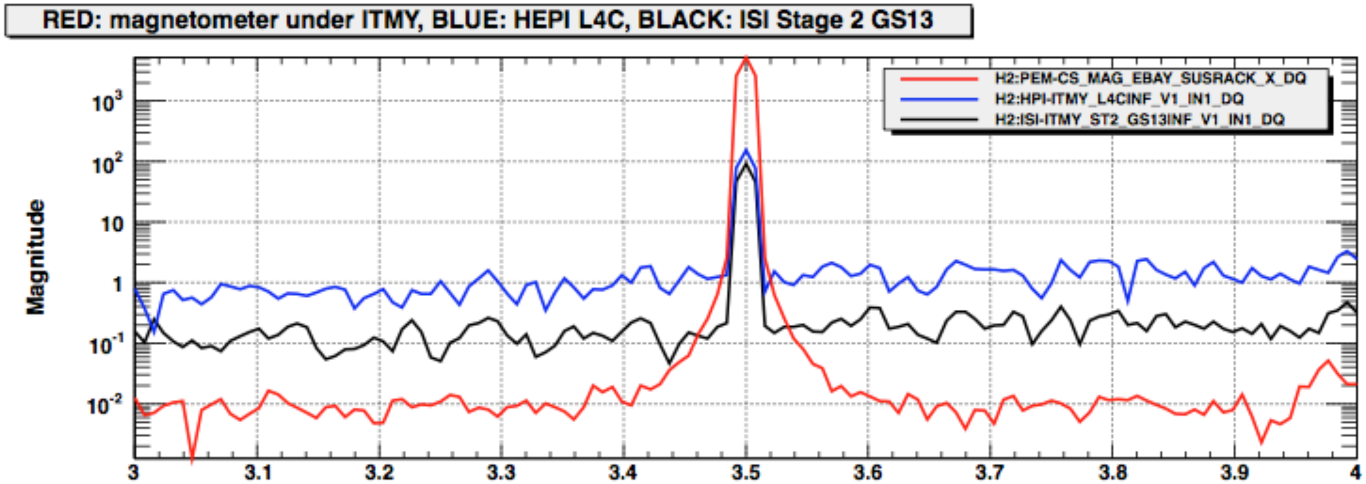
Blue: ITMY optical lever pitch

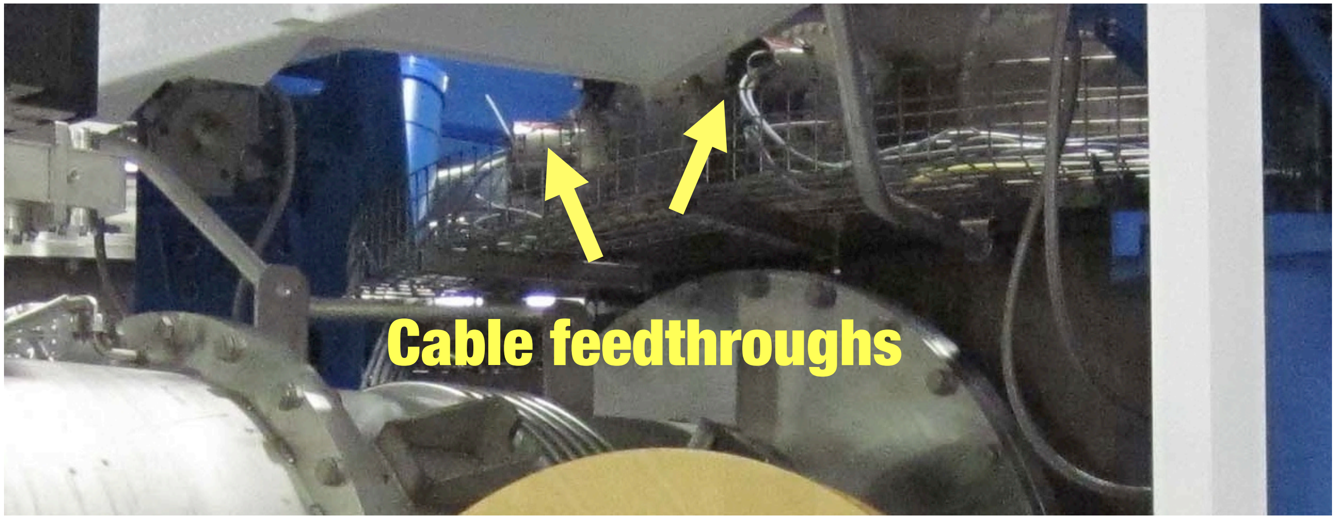
Red: OAT arm length

Black: ITMY optical lever yaw

Coupling at HEPI, ISI, SUS cables?

Injection shows up on HEPI & ISI as well as SUS channels

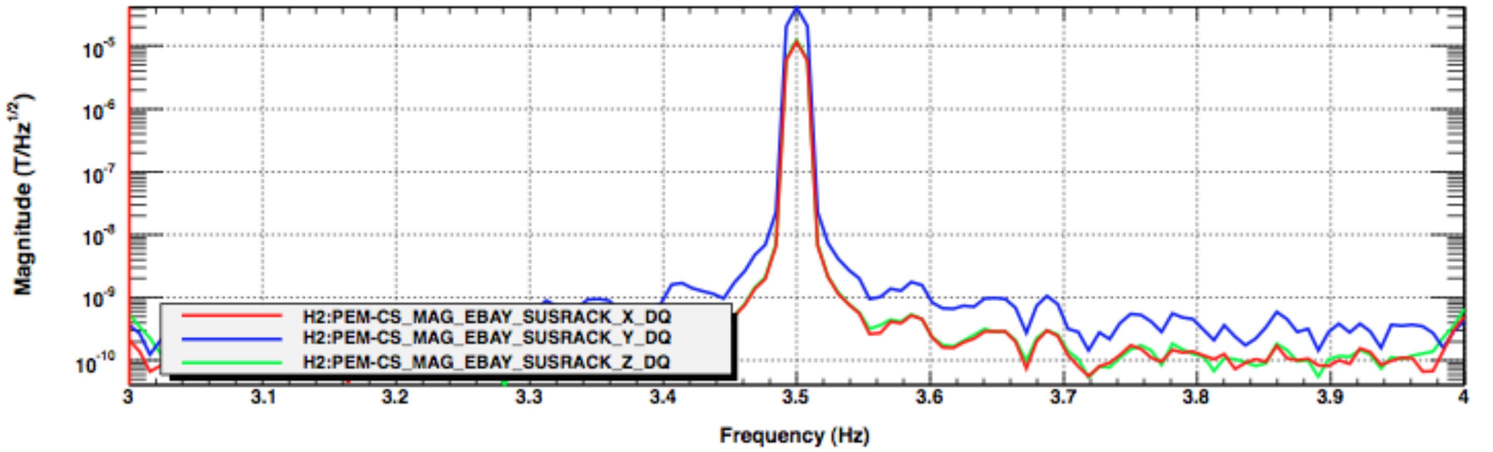

RED: magnetometer under ITMY, BLUE: HEPI L4C, BLACK: ISI Stage 2 GS13



Coupling is not to coil circuits

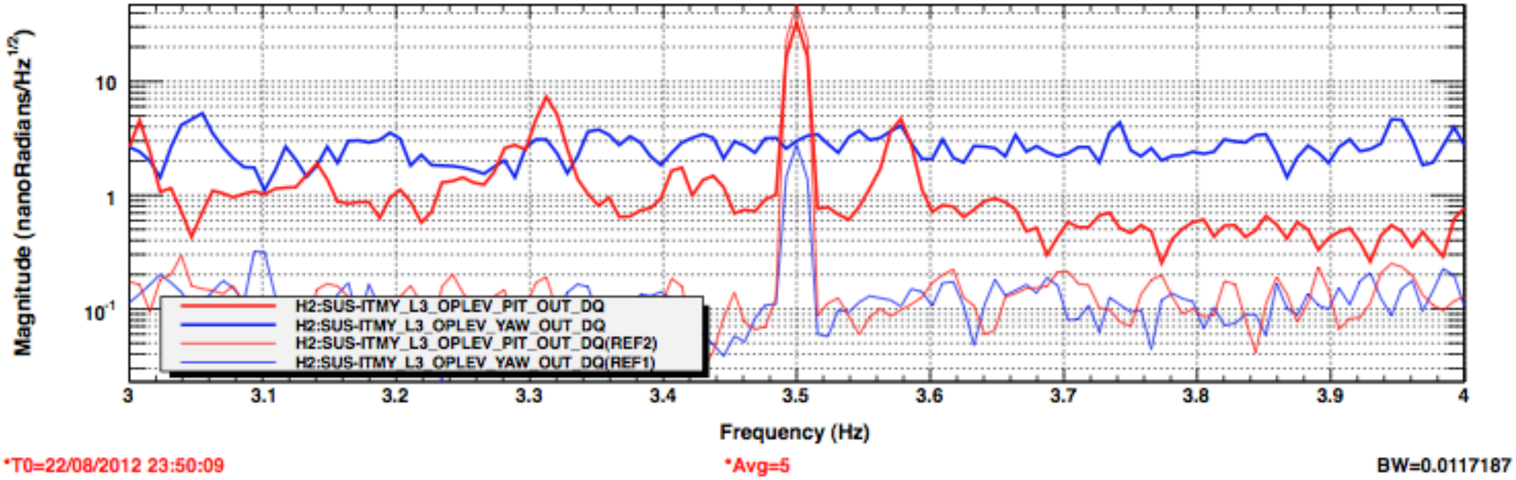
Disconnected SUS at satellite amp, ISI at coil drive, HEPI off

Magnetic field near ITMY

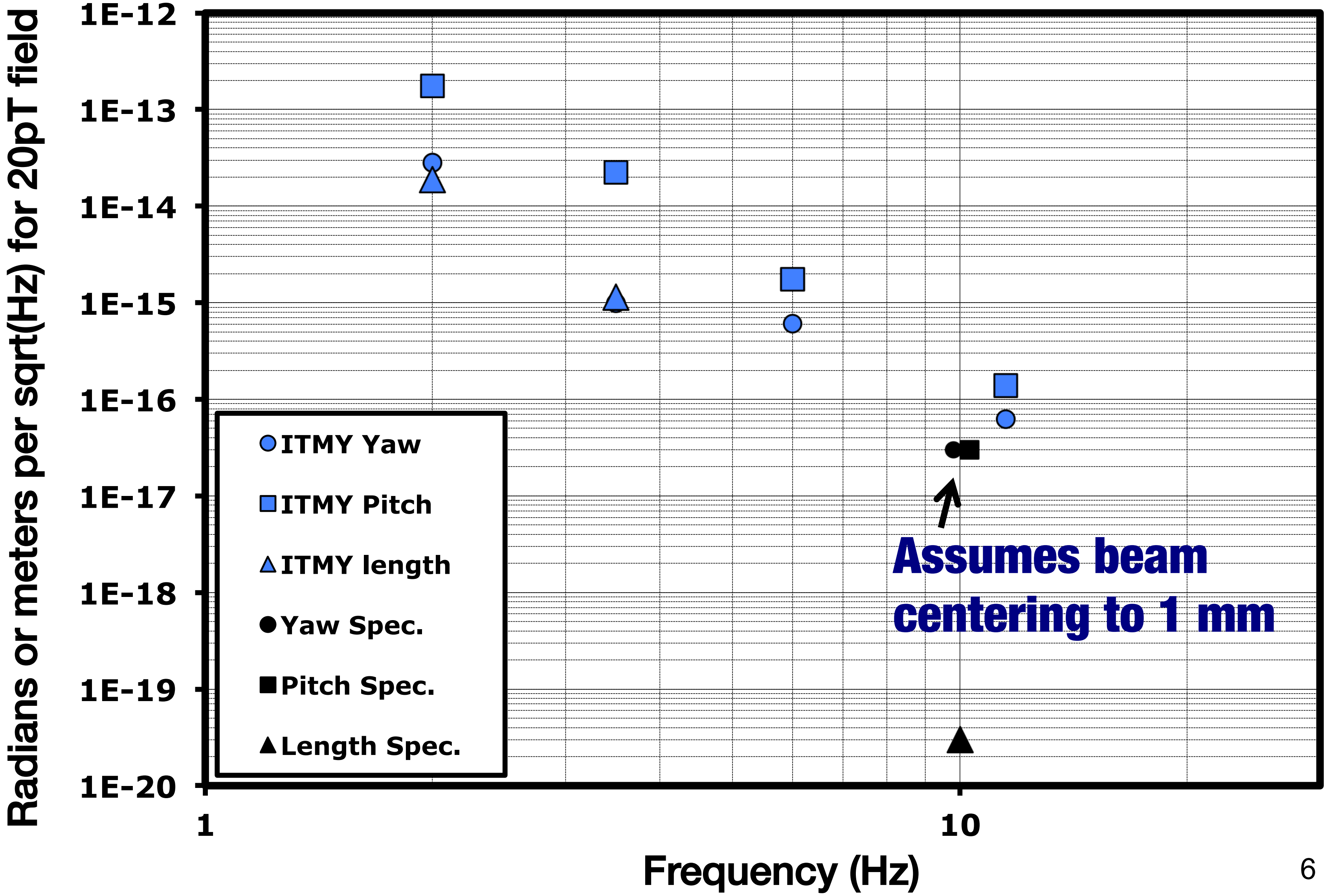


Red: pitch, Blue: yaw, Thick: disconnected, Thin: connected

Optical lever

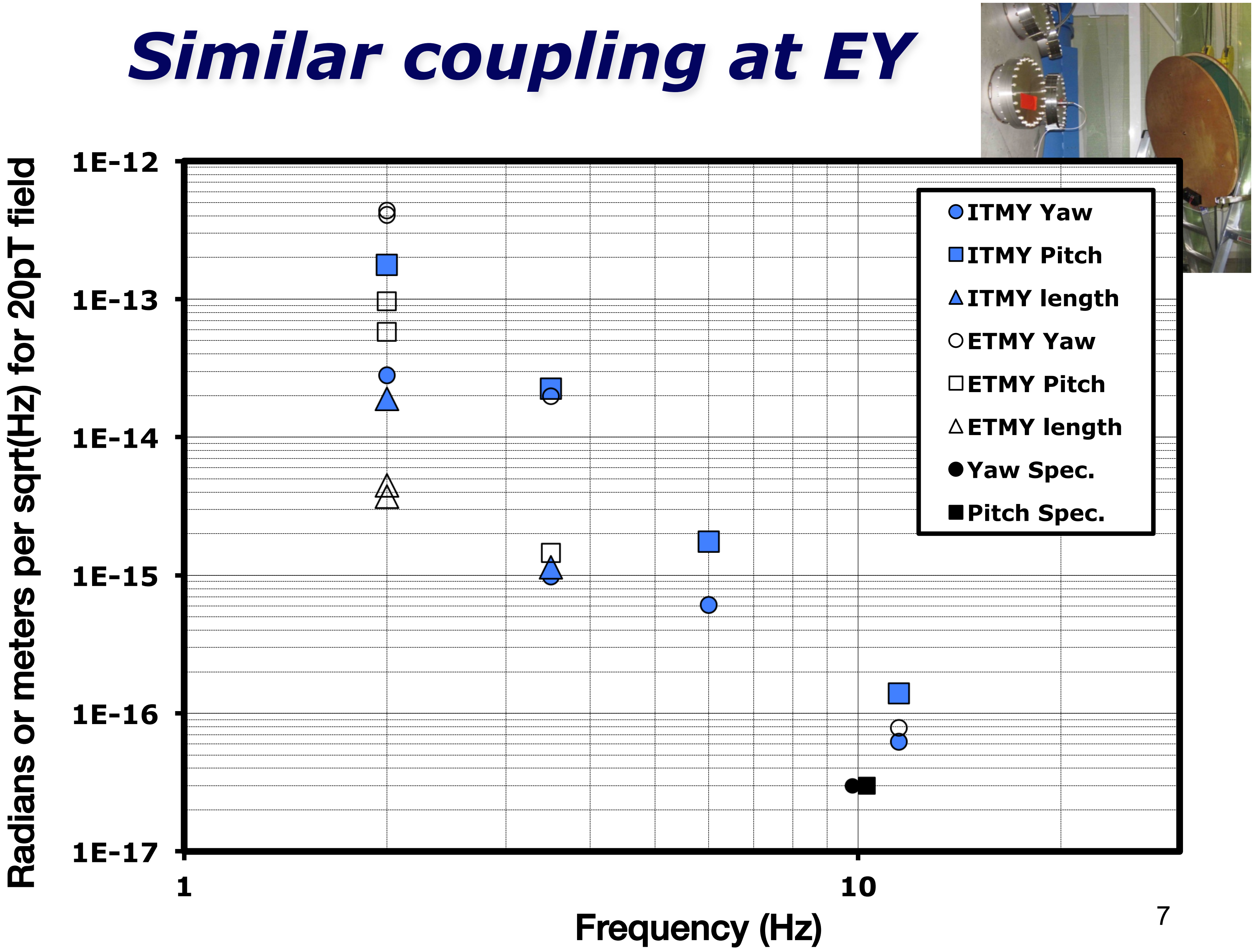


Results



Assumes beam centering to 1 mm

Similar coupling at EY

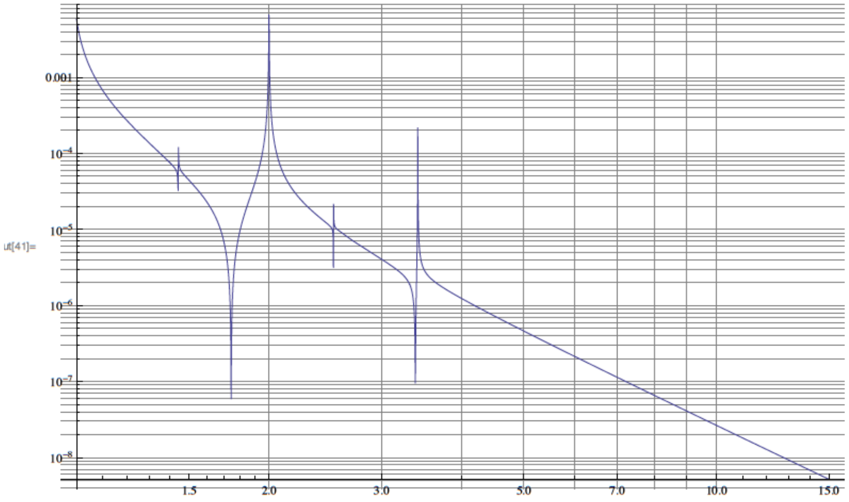


PUM to TM coupling

Force/torque at PUM to linear/angular displacement of optic

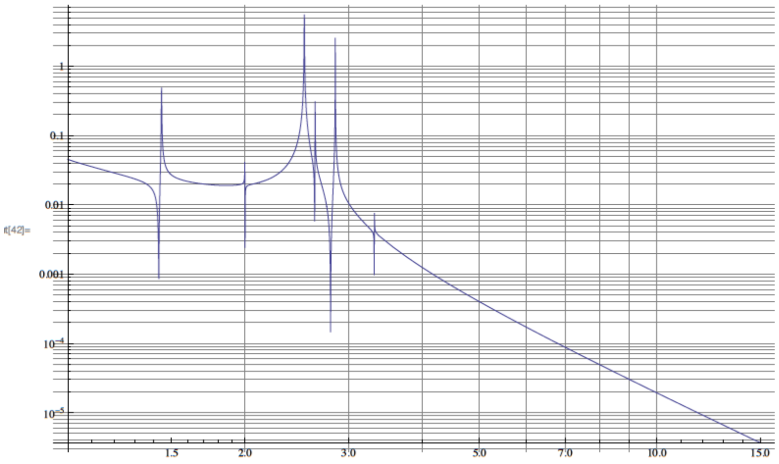
x

```
n[41]:= plotTFf[eom2, makefinputvector[x2], makeoutputvector[x3],
         1, 15, GridLines → DecadeMinorGrid, ImageSize → 600]
```



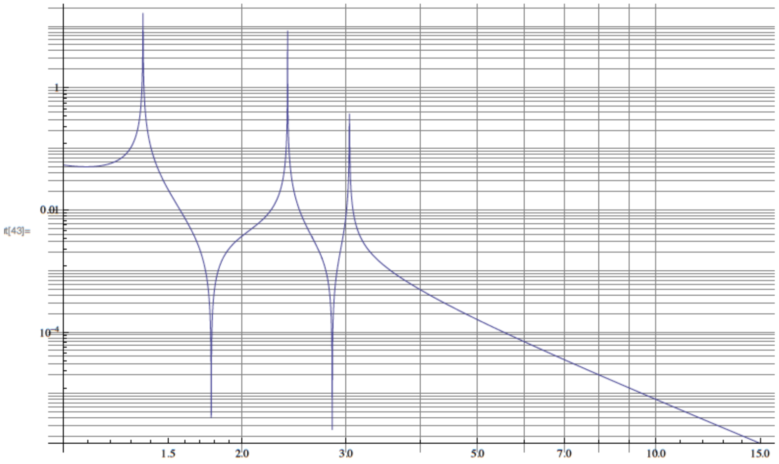
pitch

```
(42):= plotTFf[eom2, makefinputvector[pitch2], makeoutputvector[pitch3],
        1, 15, GridLines → DecadeMinorGrid, ImageSize → 600]
```



yaw

```
(43):= plotTFf[eom2, makefinputvector[yaw2], makeoutputvector[yaw3],
        1, 15, GridLines → DecadeMinorGrid, ImageSize → 600]
```



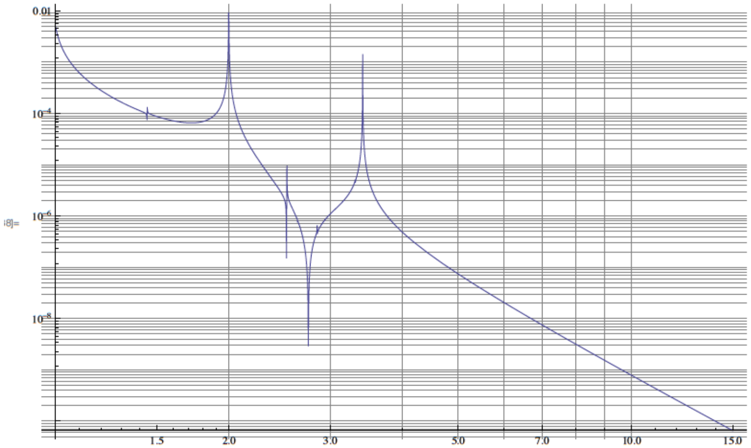
Thanks to Mark Barton

UIM to TM coupling

Force/torque at UIM to linear/angular displacement of optic

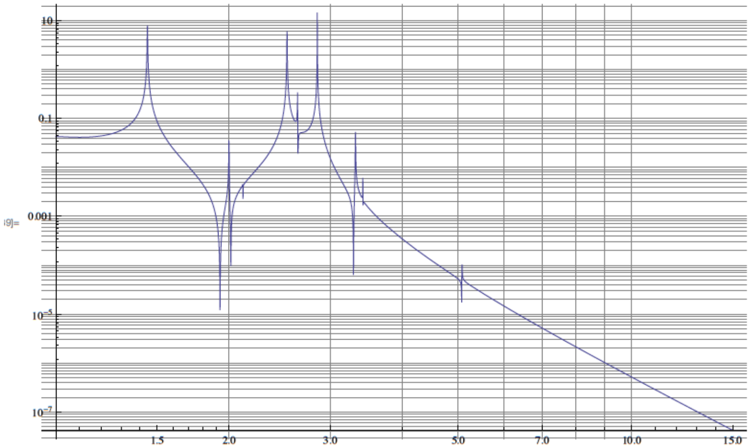
x

```
8]:= plotTFf[eom2, makefinputvector[x1], makeoutputvector[x3],
      1, 15, GridLines → DecadeMinorGrid, ImageSize → 600]
```



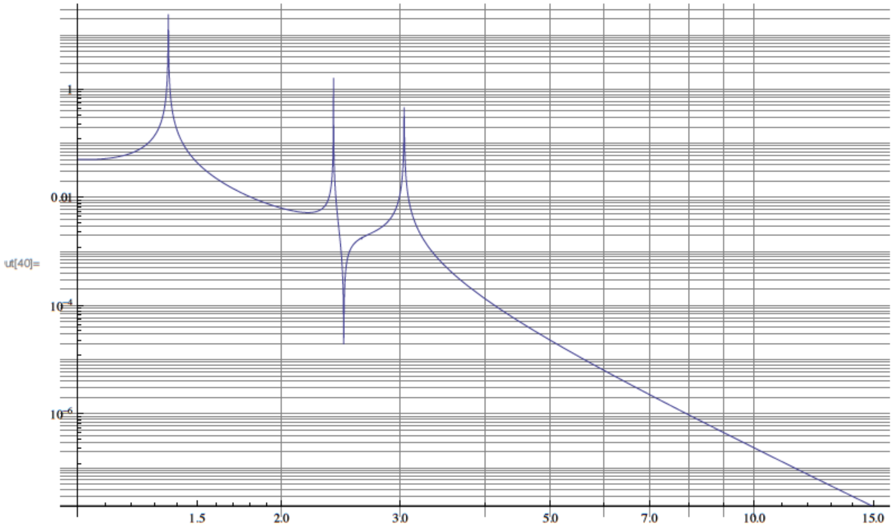
pitch

```
9]:= plotTFf[eom2, makefinputvector[pitch1], makeoutputvector[pitch3],
      1, 15, GridLines → DecadeMinorGrid, ImageSize → 600]
```



yaw

```
In[40]:= plotTFf[eom2, makefinputvector[yaw1], makeoutputvector[yaw3],
          1, 15, GridLines → DecadeMinorGrid, ImageSize → 600]
```



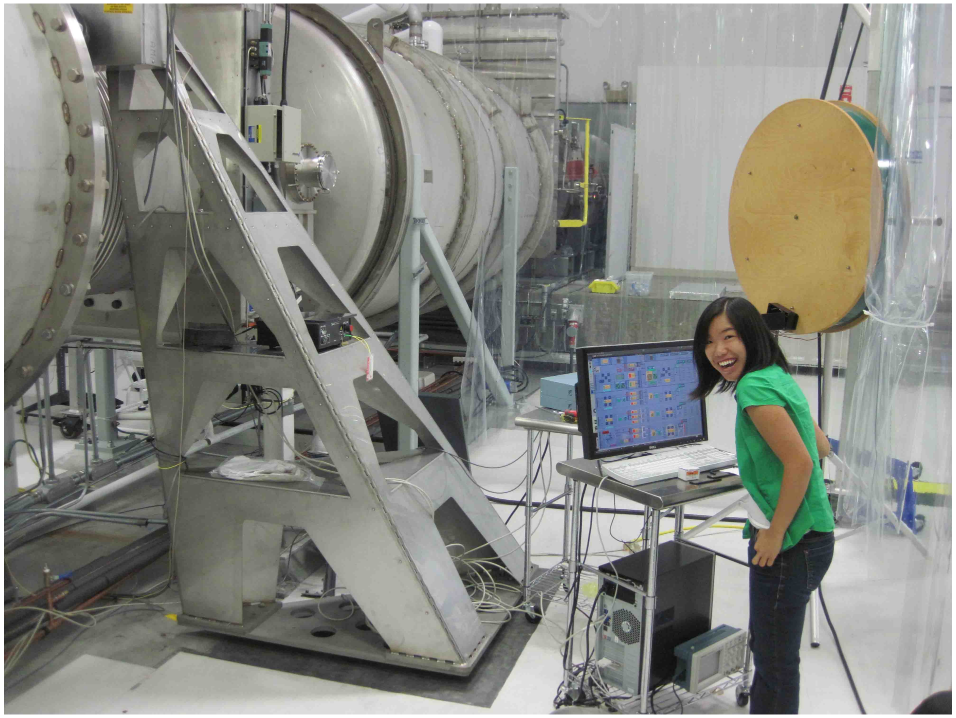
Thanks to Mark Barton

Checks

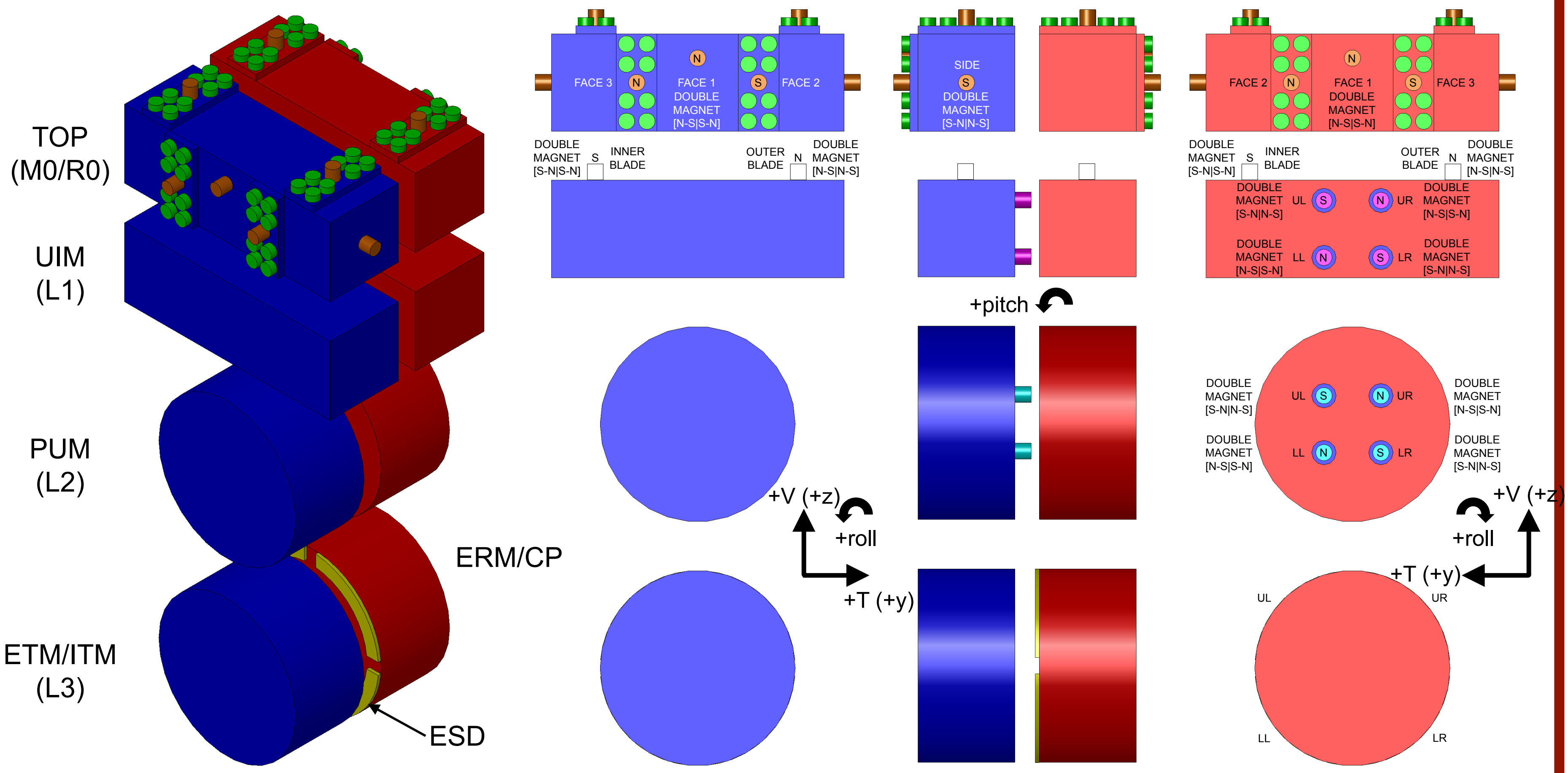
1) Coupling to optical lever? Much higher fields at optical lever and its electronics produced smaller peak in optical lever channel.

2) Linear coupling? Increased field by 2.98 increased motion by 3.00 (would go as B^2 for induced moments).

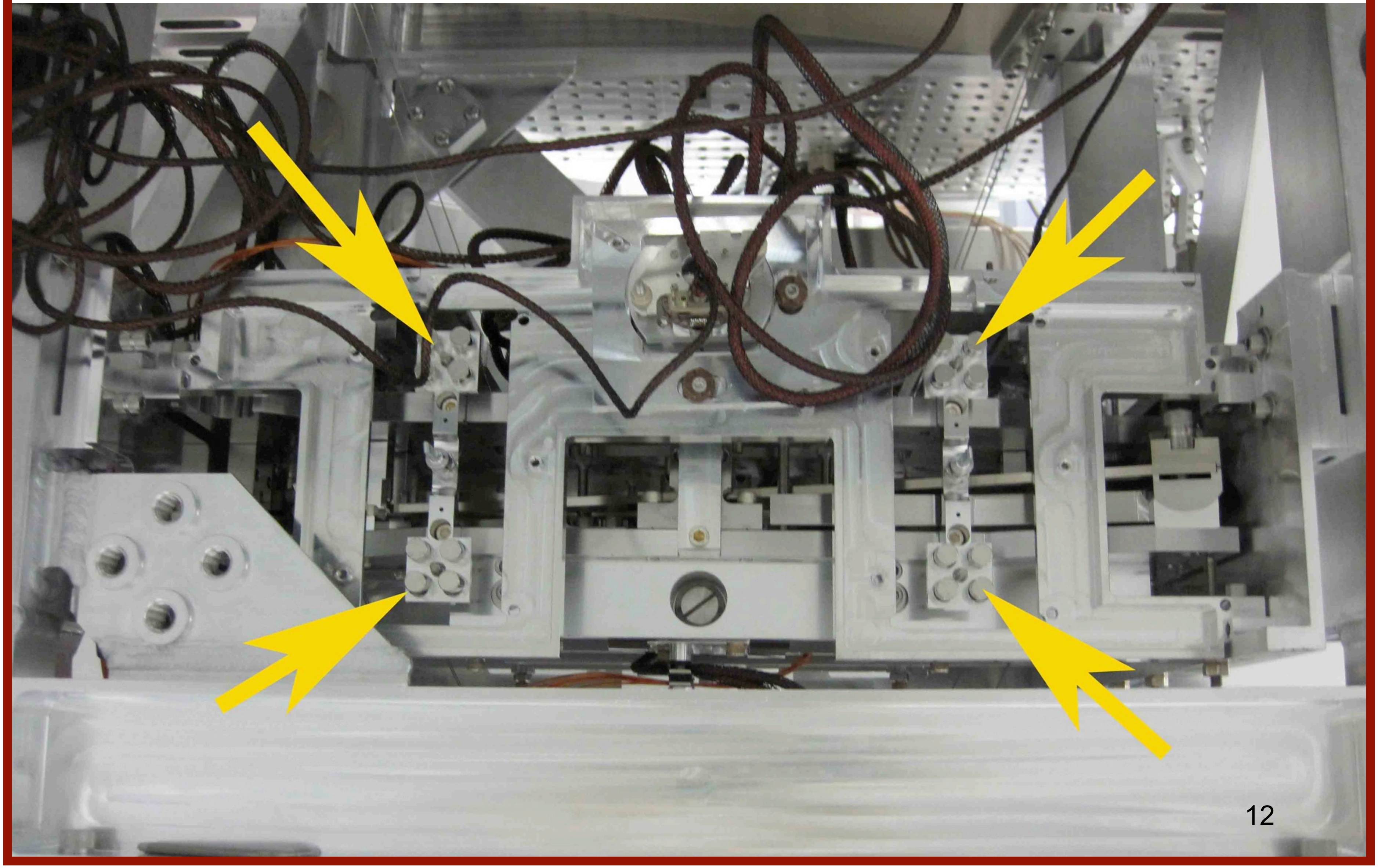
3) Calibration? In-situ magnetometer calibration



Quad magnets



Removing M0 ECDs

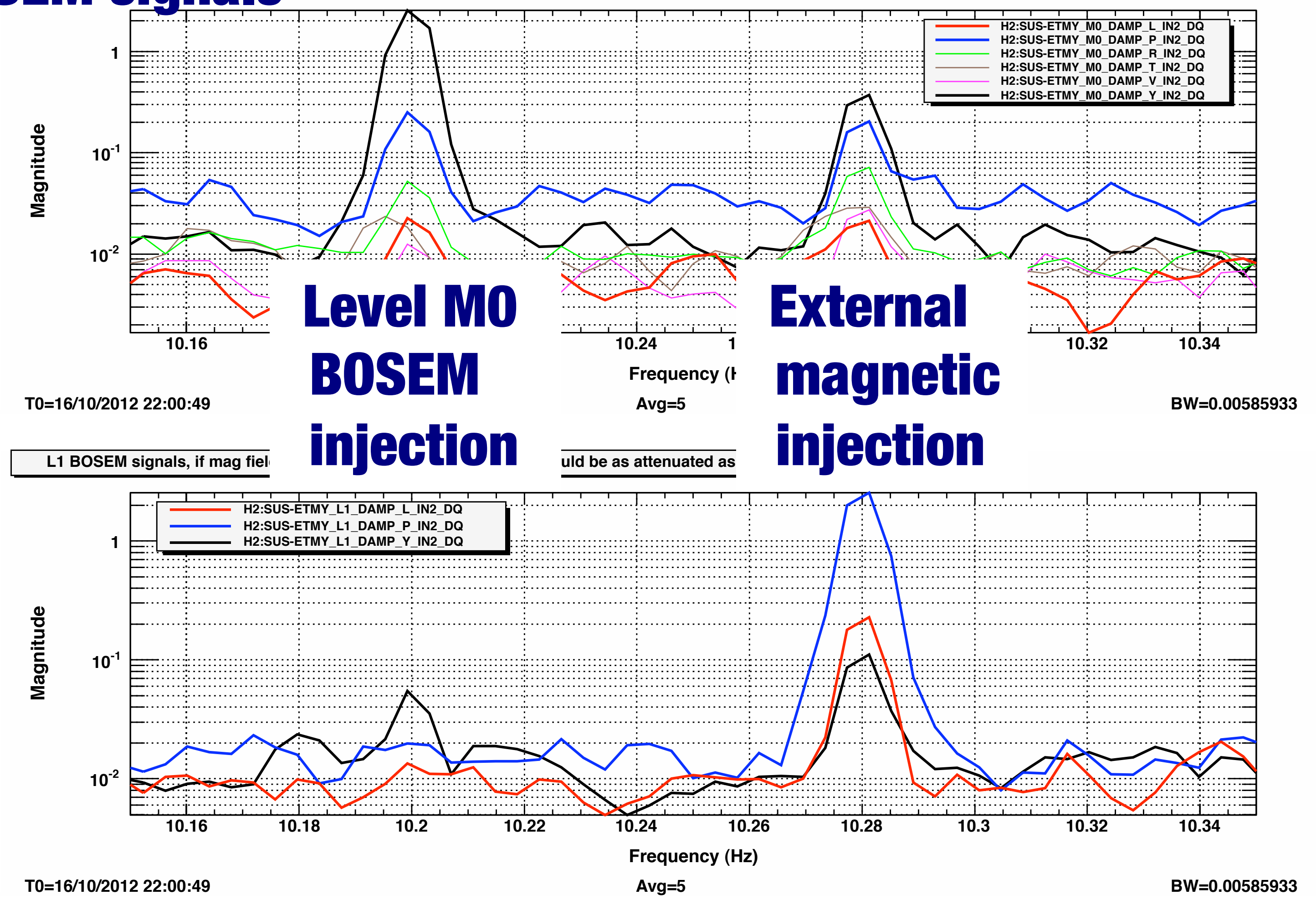


Coupling at multiple levels

BOSEM signals

M0

L1

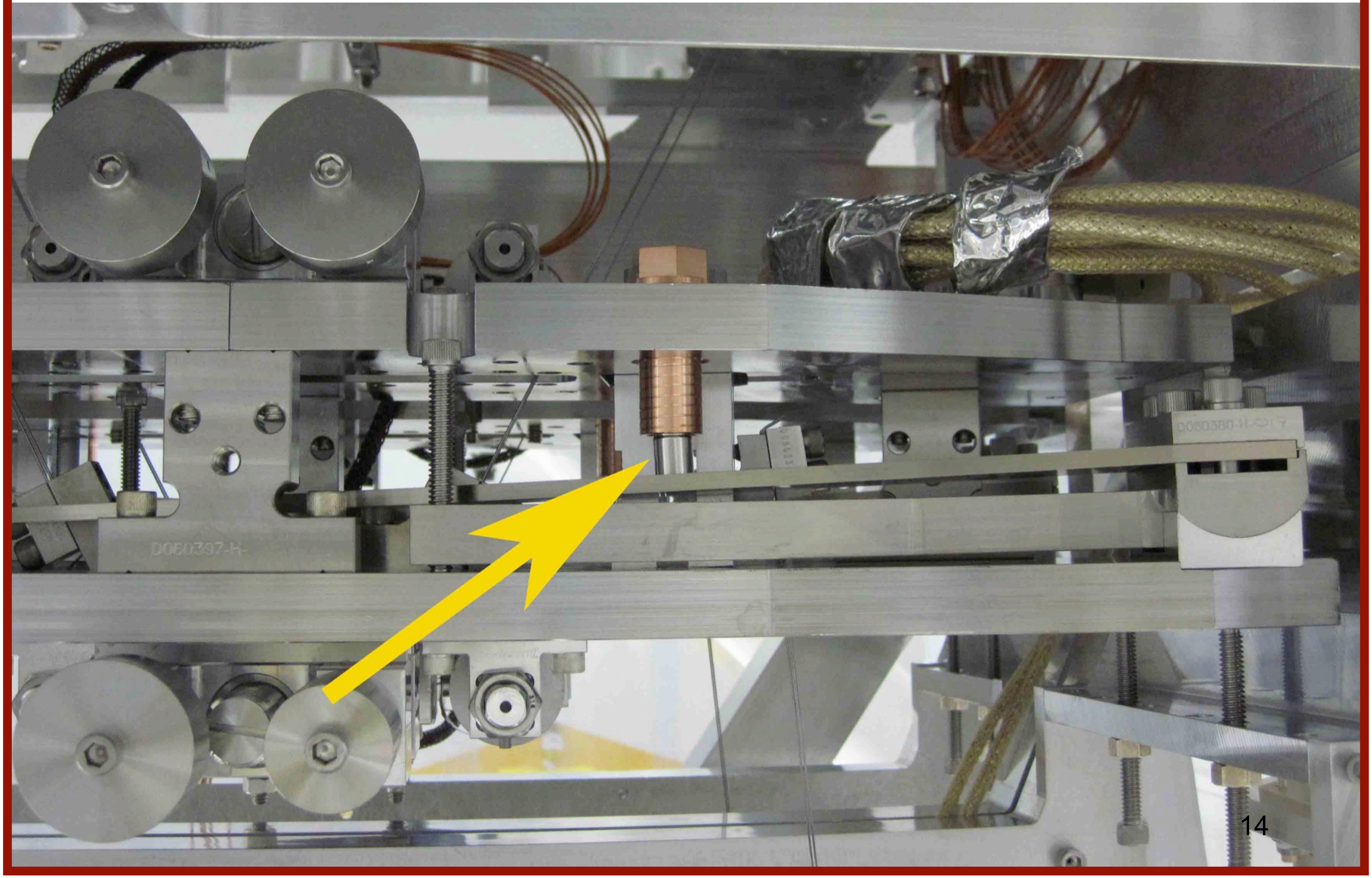


Level M0 BOSEM injection

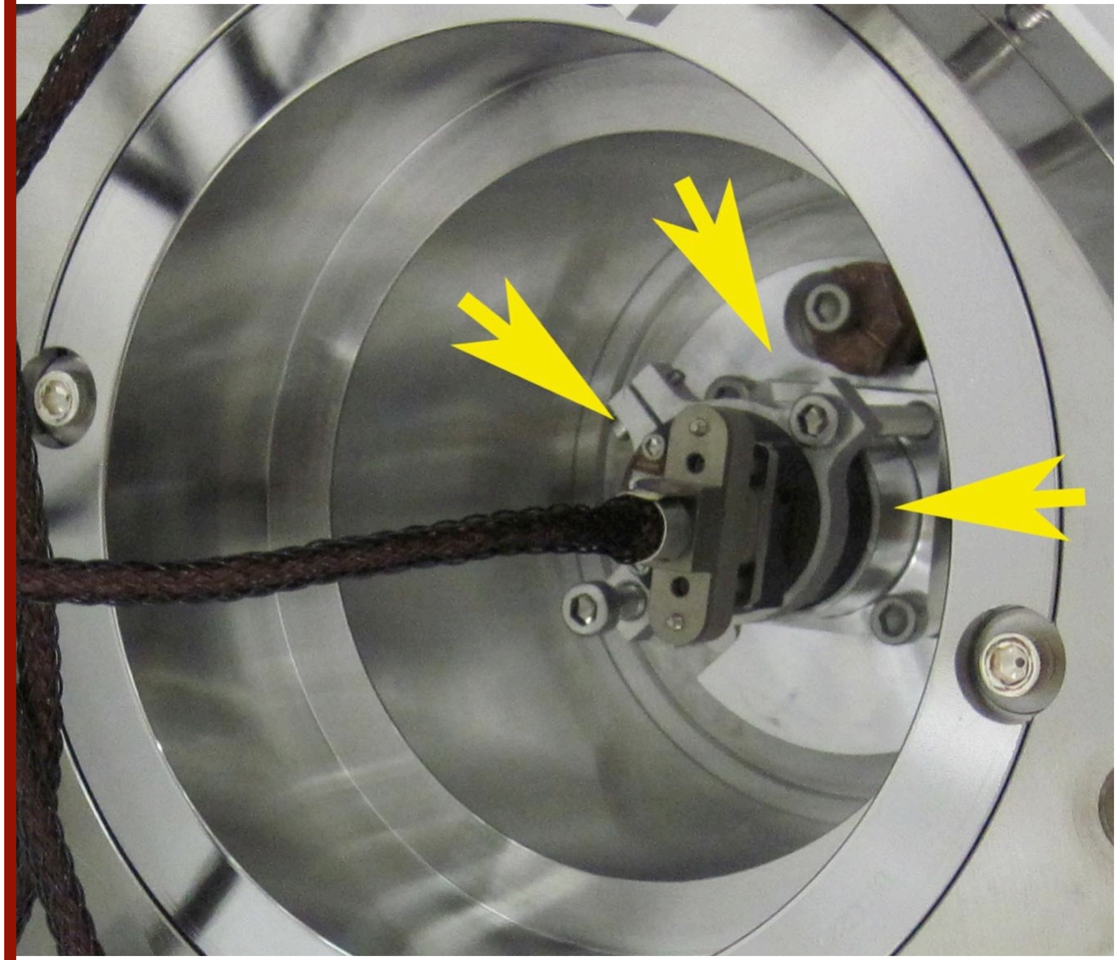
External magnetic injection

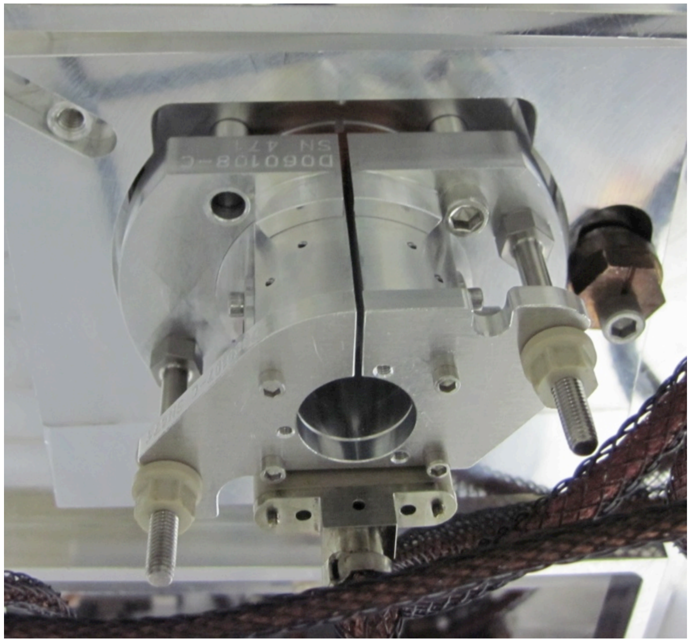
If coupling were only at M0, at L0 the two signals would be equally attenuated

Removal of L1(UIM) blade dampers



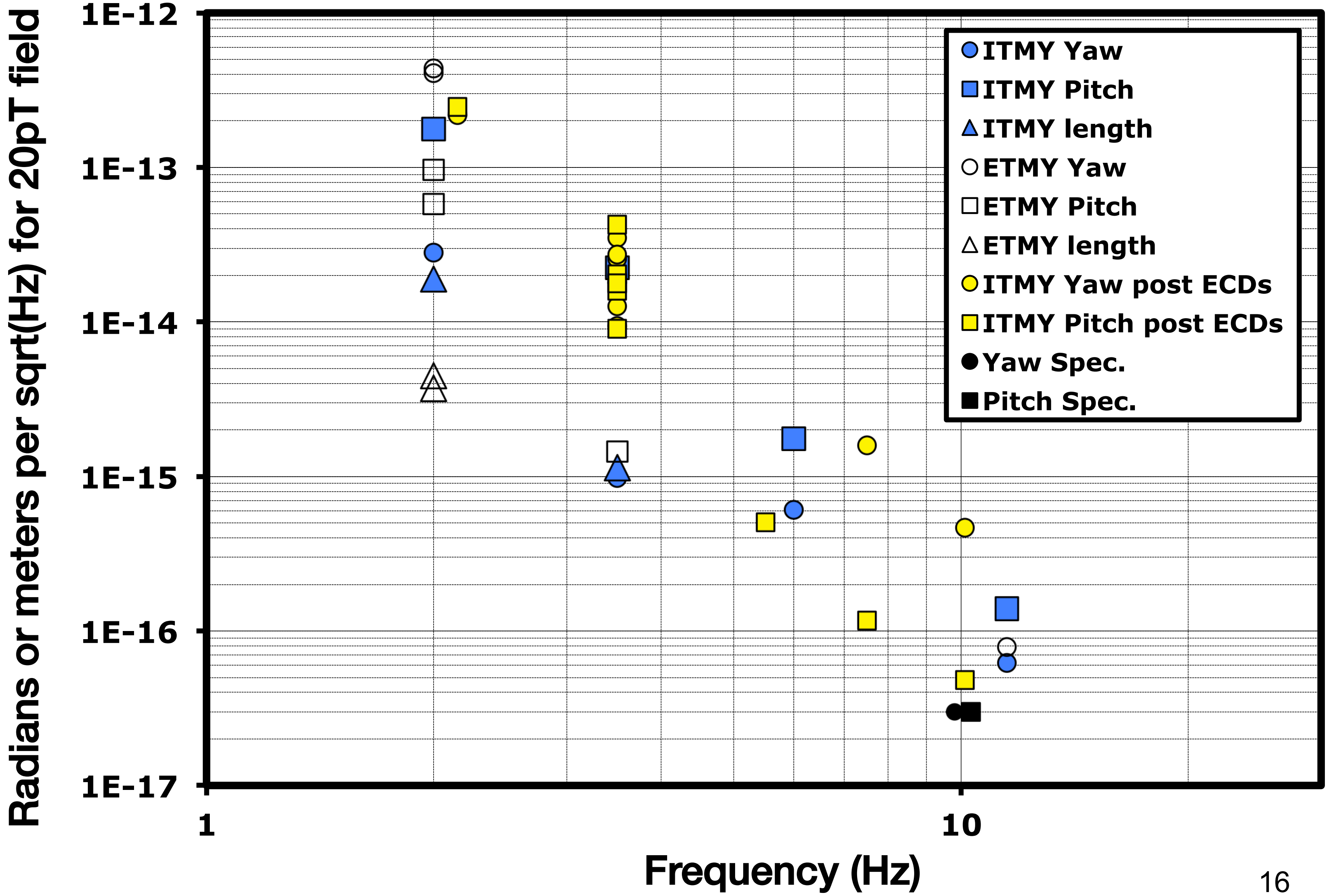
Suggested AOSEM cuts to reduce eddy current coupling (not tested yet)





BOSEMs are already slit

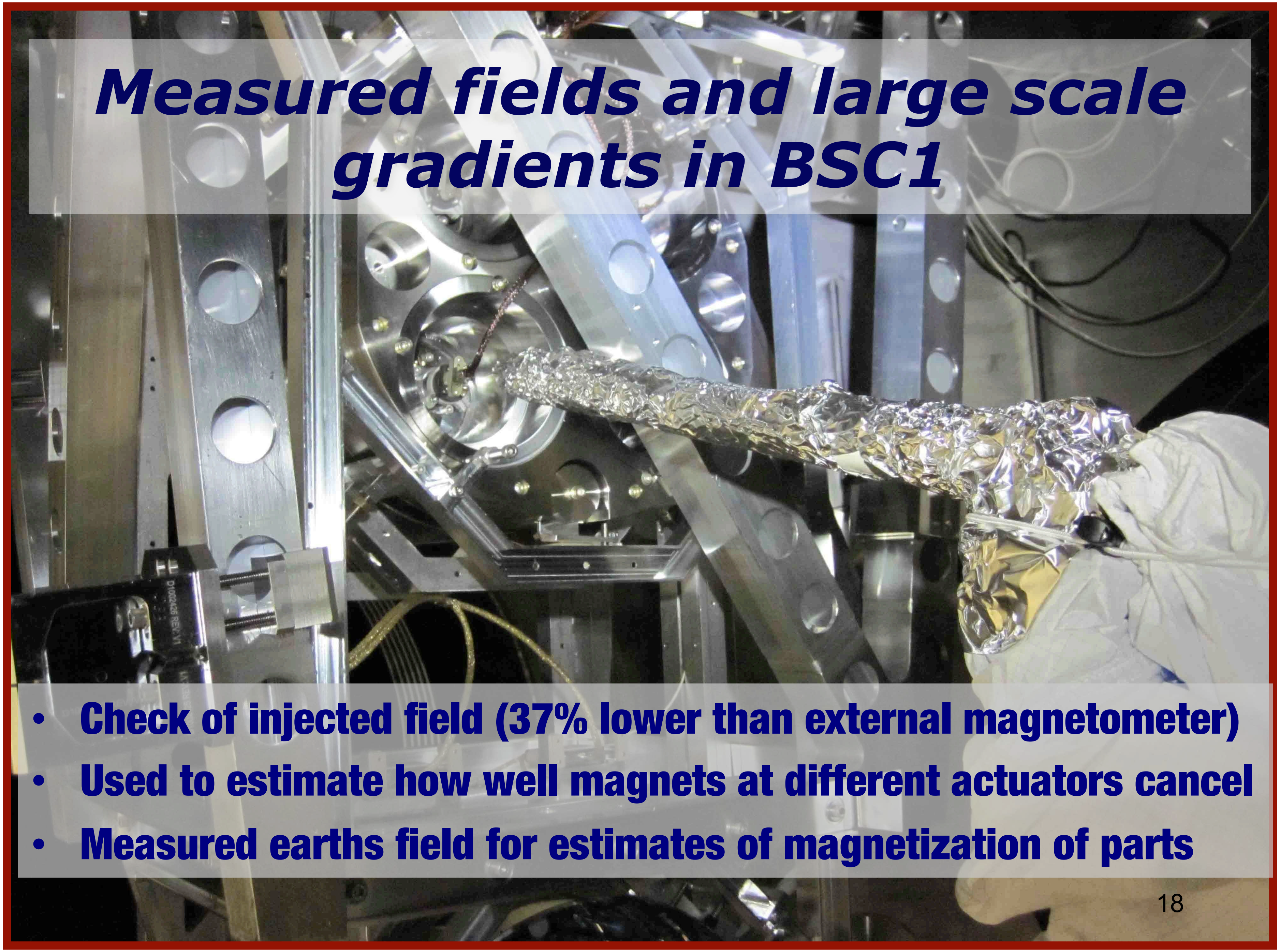
Results after ECD removal



Measurements of gradients at PUM magnet locations

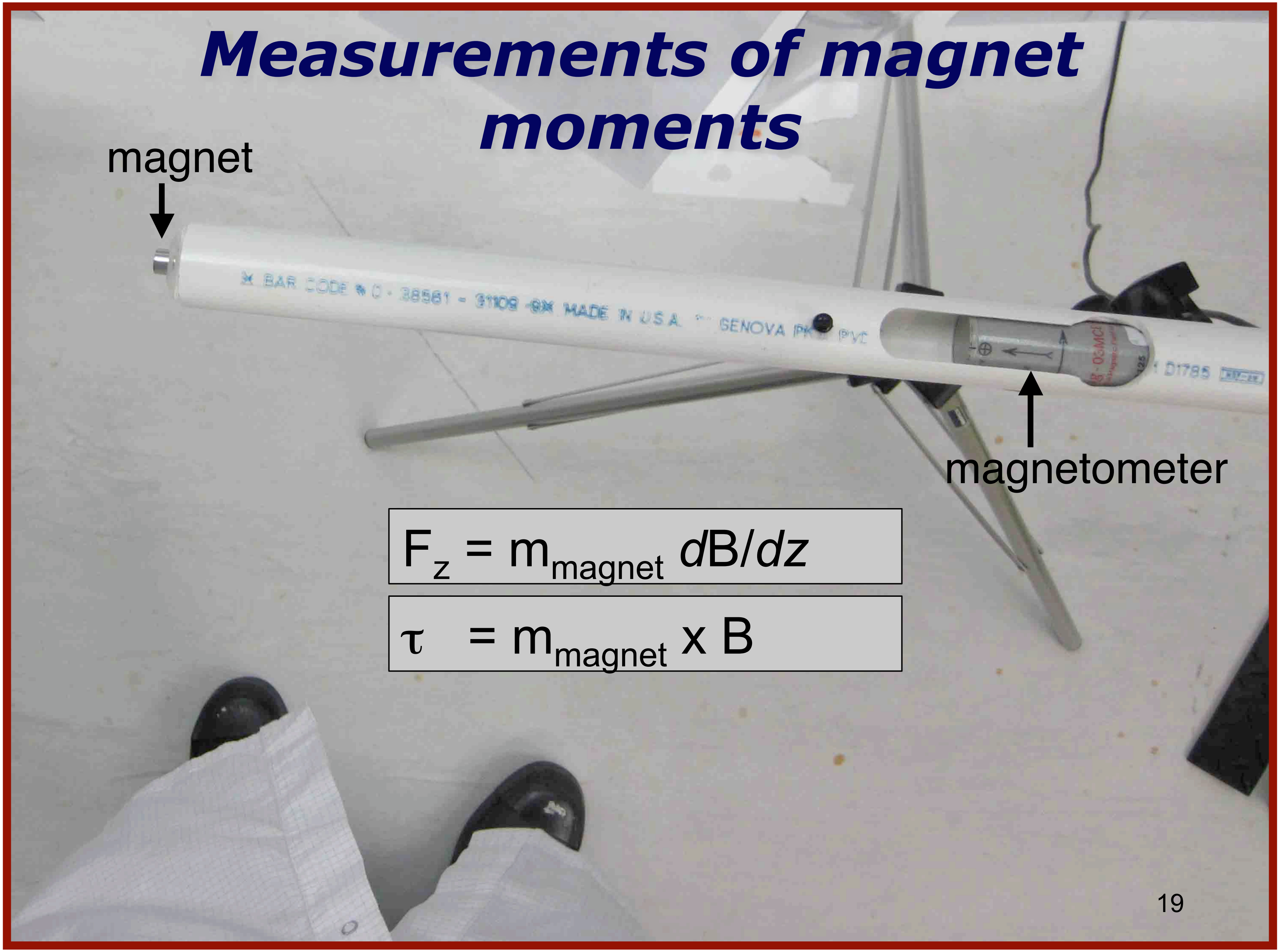
$F_z = m_{magnet}\, dB/dz$

Measured fields and large scale gradients in BSC1



- Check of injected field (37% lower than external magnetometer)
- Used to estimate how well magnets at different actuators cancel
- Measured earths field for estimates of magnetization of parts

Measurements of magnet moments



$$F_z = m_{\text{magnet}}\, dB/dz$$

$$\tau = m_{\text{magnet}} \text{ x } B$$

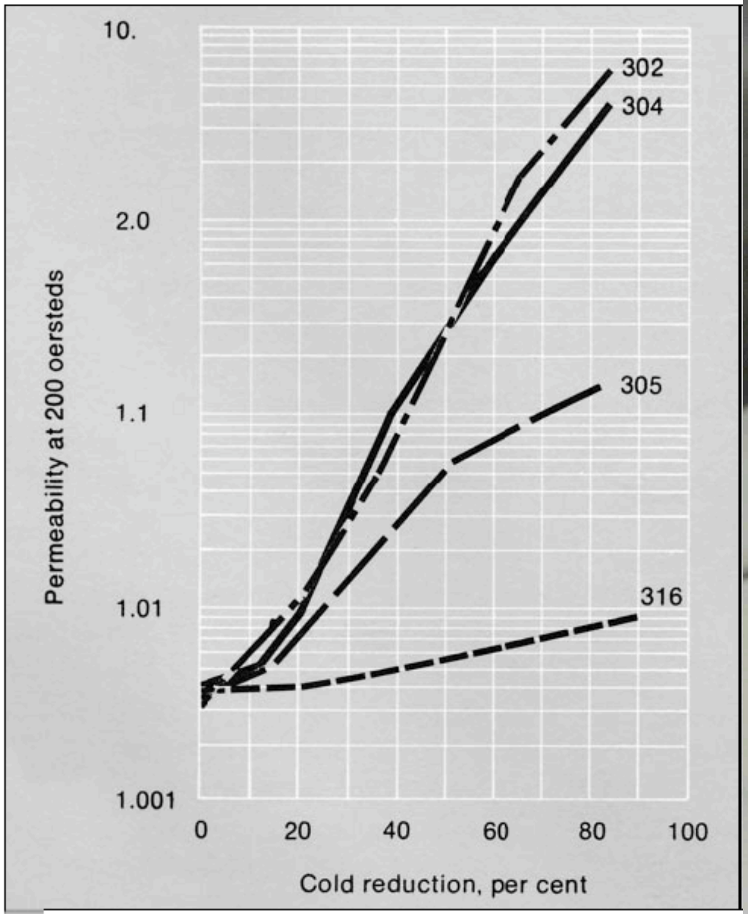
Measurements combined to estimate motion from coupling to magnets

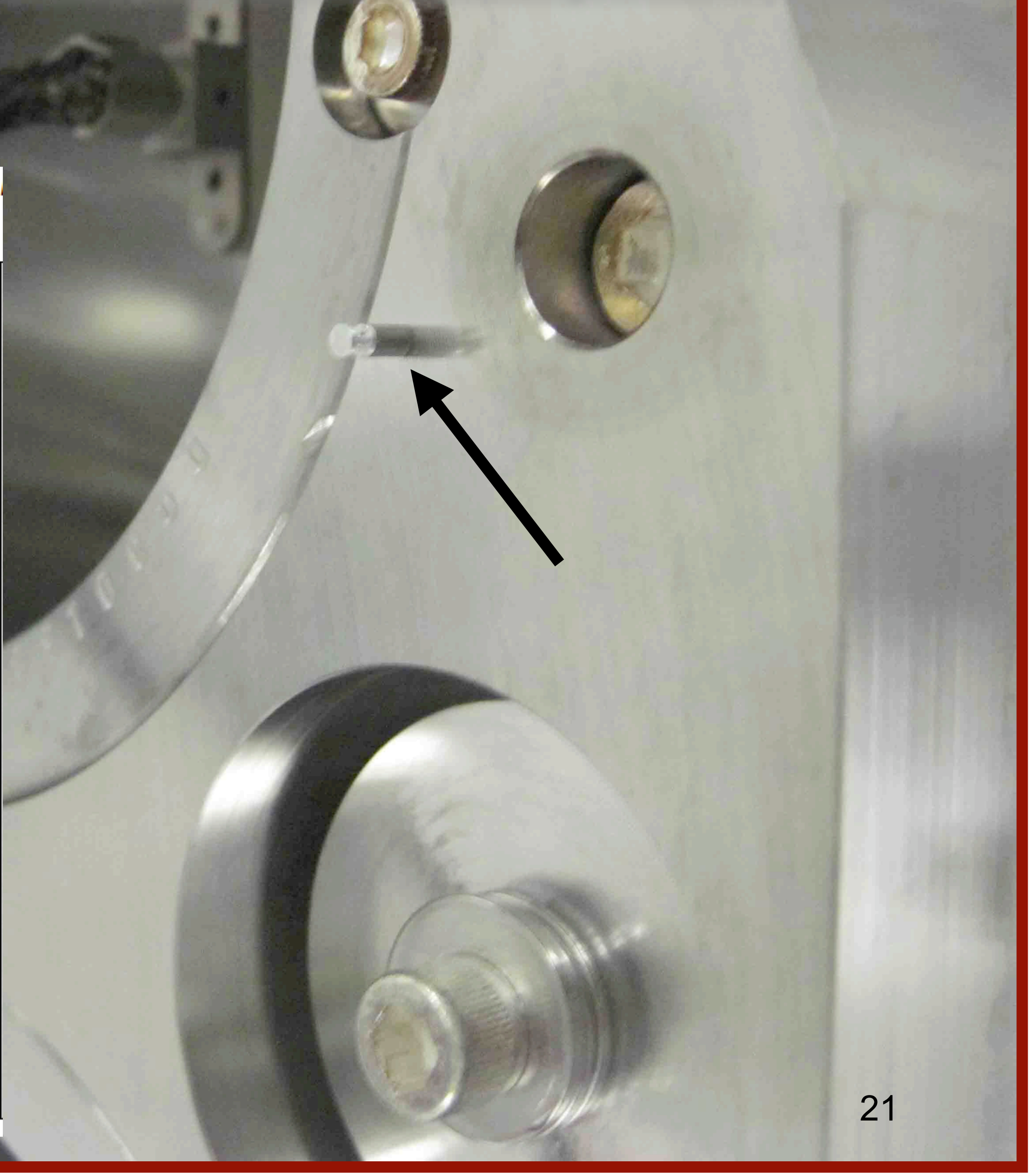
Yellow estimates exceed spec.

Magnets	**Motion assuming magnets all oriented correctly (moment * 0.3)** Assuming 20pT ambient field with B/gradB = 0.06 m	**One magnet flipped (moment * 2)**	**Worst case conspiracy (moment * 8)**
UIM magnets Magnet moment: 0.72 J/T. Moment arm for angular motion from gradients – pitch: 0.07 m, yaw: 0.13 m	**Pos: 5.7e-20** Pit (grad): 2.5e-18 Pit (field): 2.2e-18 Yaw (grad): 2.0e-18 Yaw (field): 9.5e-19	**Pos: 3.8e-19** Pit (grad): 1.7e-17 Pit (field): 1.4e-17 Yaw (grad): 1.3e-17 Yaw (field): 6.3e-18	**Pos: 1.5 e-18** **Pit (grad): 6.7 e-17** **Pit (field): 5.7 e-17** **Yaw (grad): 5.3 e-17** Yaw (field): 2.5 e-17
PUM magnets Magnet moment: 0.013 J/T. Moment arm for angular motion from gradients - pitch and yaw: 0.15 m	**Pos: 3.25e-20** Pit (grad): 3.9e-18 Pit (field): 1.6e-18 Yaw (grad): 1.6e-18 Yaw (field): 6.2e-19	**Pos: 2.2e-19** Pit (grad): 2.6e-17 Pit (field): 1.0e-17 Yaw (grad): 1.0e-17 Yaw (field): 4.2e-18	**Pos: 8.7 e-19** **Pit (grad): 1.0 e-16** **Pit (field): 4.2 e-17** **Yaw (grad): 4.2 e-17** Yaw (field): 1.7 e-17

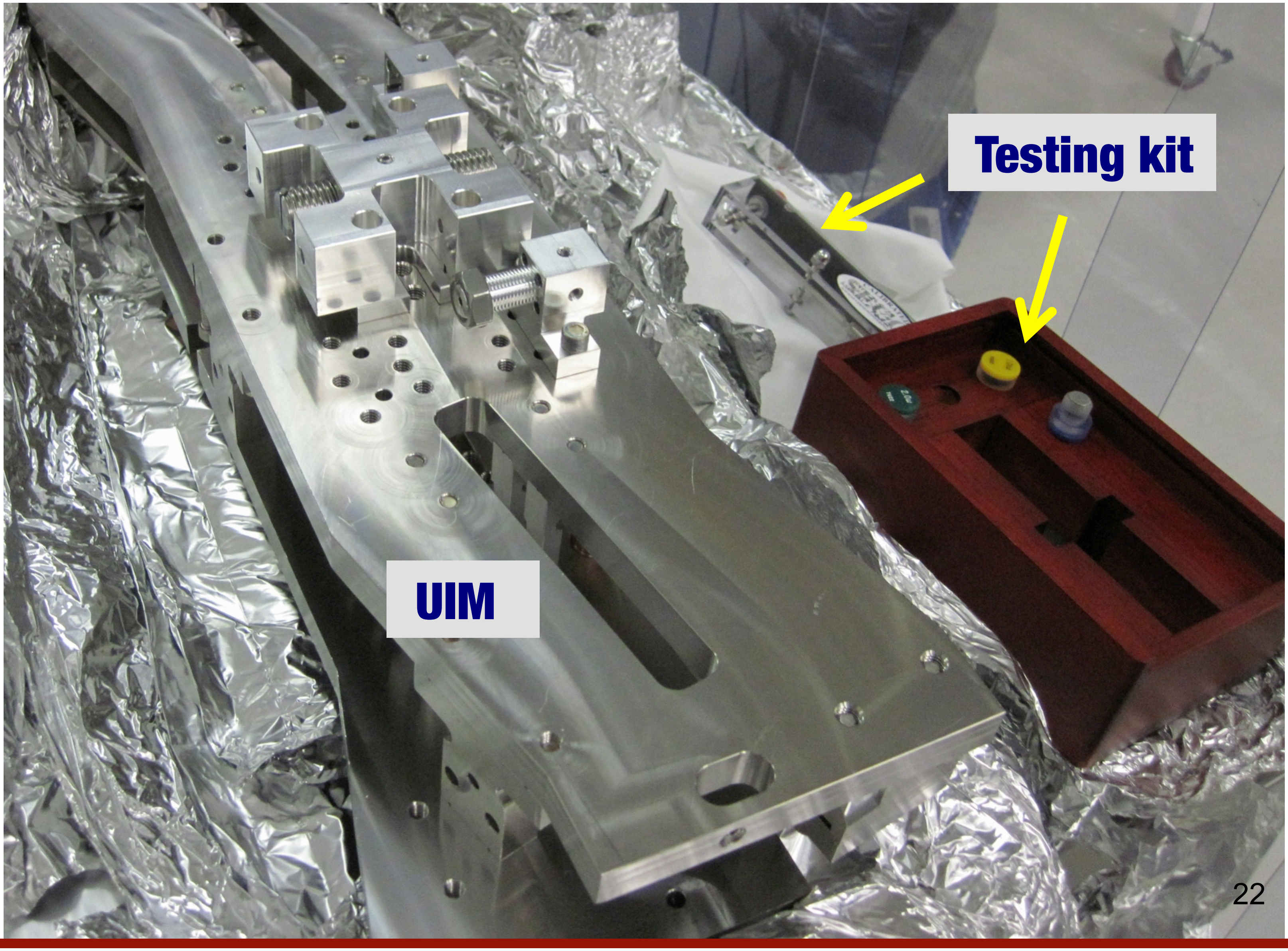
Other magnetic quad components

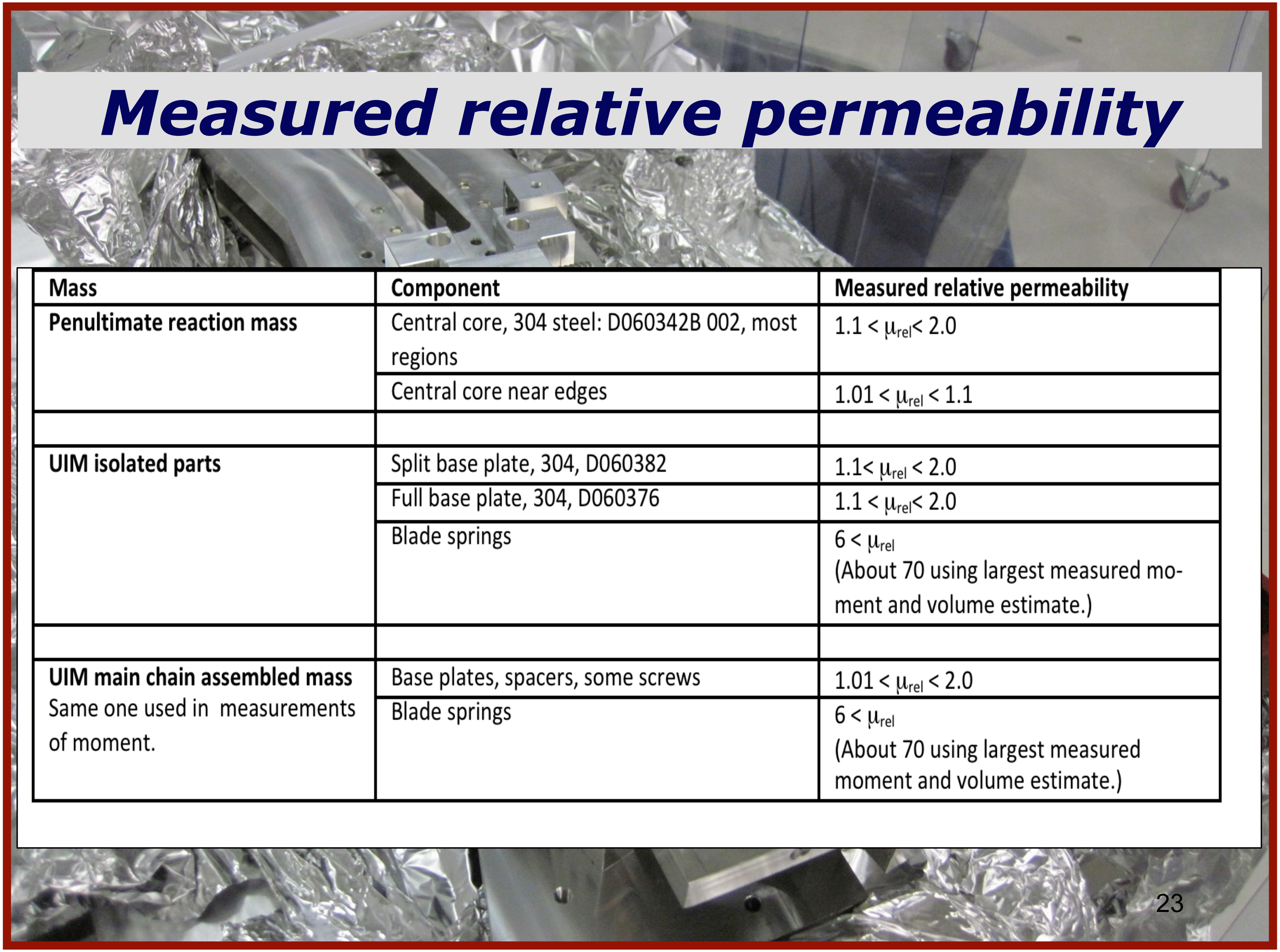
Figure 7 **WHEN COLD WORKING IS EMPLOYED, SOME NORMALLY NON-MAGNETIC AUSTENITIC STEELS BECOME SUBSTANTIALLY MAGNETIC**





Relative permeability measurements





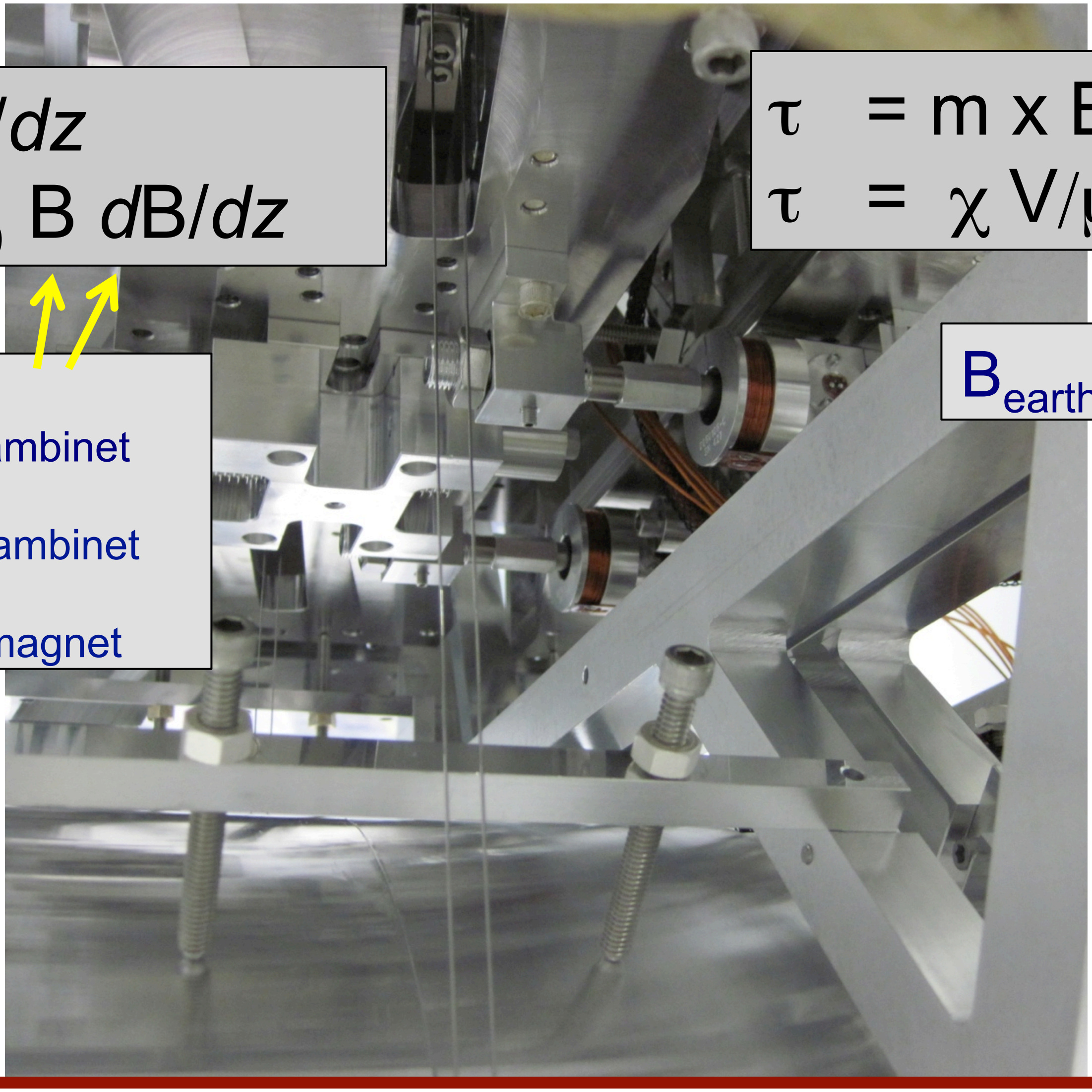
Measured relative permeability

Mass	Component	Measured relative permeability
Penultimate reaction mass	Central core, 304 steel: D060342B 002, most regions	$1.1 < \mu_{rel} < 2.0$
	Central core near edges	$1.01 < \mu_{rel} < 1.1$
UIM isolated parts	Split base plate, 304, D060382	$1.1 < \mu_{rel} < 2.0$
	Full base plate, 304, D060376	$1.1 < \mu_{rel} < 2.0$
	Blade springs	$6 < \mu_{rel}$ (About 70 using largest measured moment and volume estimate.)
UIM main chain assembled mass Same one used in measurements of moment.	Base plates, spacers, some screws	$1.01 < \mu_{rel} < 2.0$
	Blade springs	$6 < \mu_{rel}$ (About 70 using largest measured moment and volume estimate.)

Measuring magnetic moment

Balance offloads most weight, mg scale measures change in force as magnetic field is turned off and on

Coupling mechanisms to paramagnetic parts



$F_z = m\, dB/dz$

$F_z = \chi V/\mu_0\ B\, dB/dz$

$\tau\ = m \times B$

$\tau\ = \chi V/\mu_0\ B\ B$

B_{earth} $d\tilde{B}_{ambinet}$

B_{magnet} $d\tilde{B}_{ambinet}$

$\tilde{B}_{ambient}$ dB_{magnet}

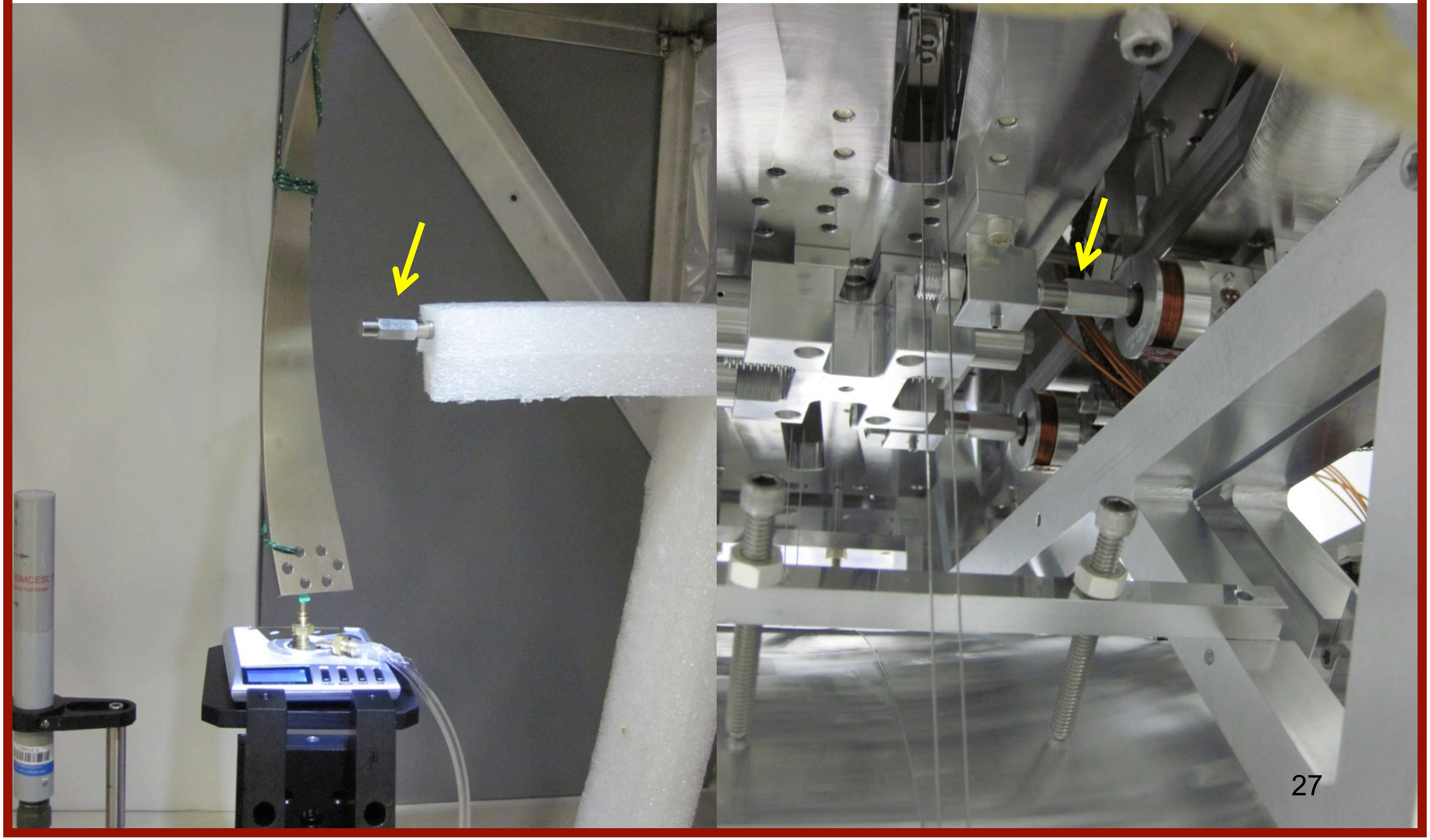
B_{earth} $\tilde{B}_{ambient}$

Ambient fields coupling to parts magnetized by earths field

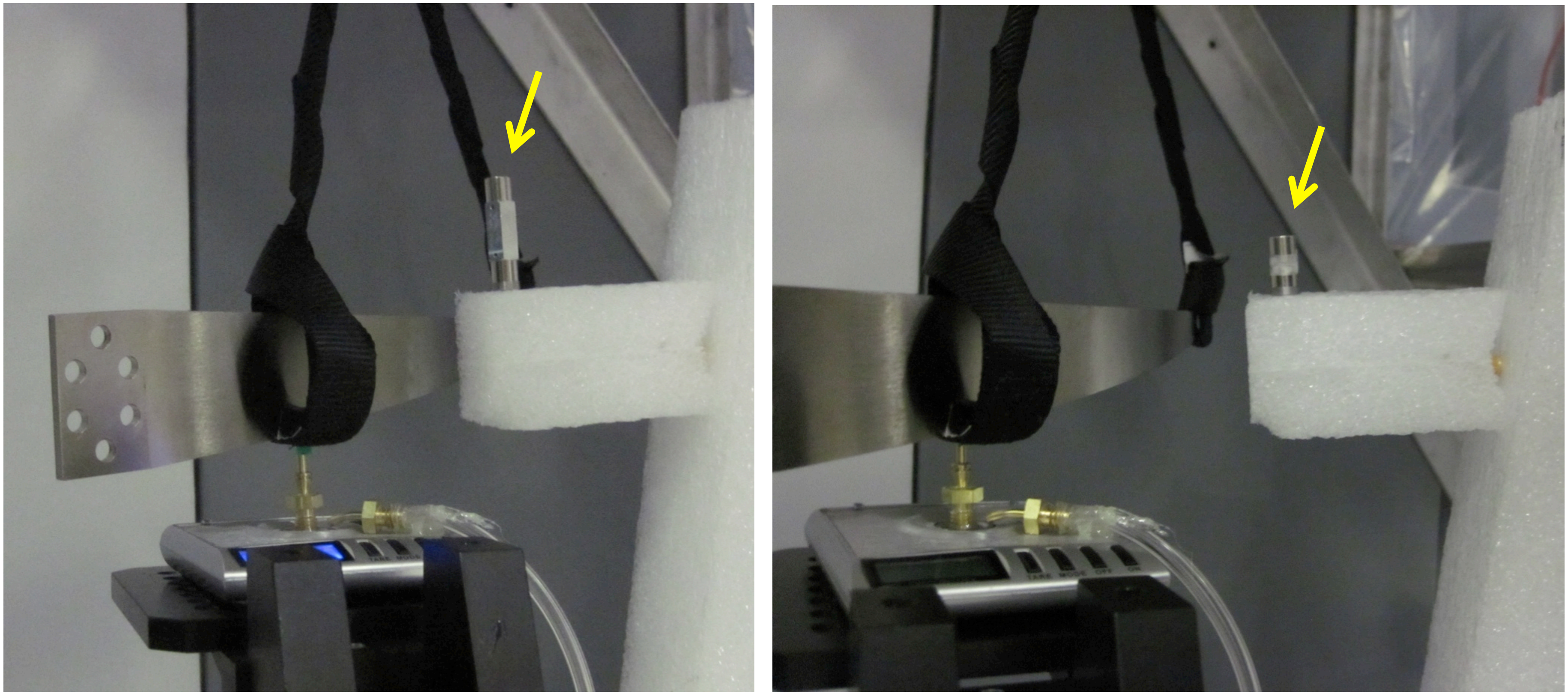
Sample	**Estimated induced moment in BSC1**	**Estimated test mass motion at 10 Hz**	**Consistency/ accuracy checks:**
	From induced moment measured in test hutch (using ~ 1.5 e-4 T) and measured earth's field in BSC1. (J/T) *Earths field in BSC1:* *X: 1.07 e-5 T* *Y: -1.63 e-5 T* *Z: -3.56 e-5 T* *Beam along Y*	From varying ambient gradients (pos) or fields (pit, yaw) assuming 20pT ambient field with B/gradB = 0.06 m (m, rad, rad)	magnets of known moment were added (J/T)
PUM reaction mass 304 central piece (end pieces were 316)	Y: 0.006±0.005 Z: 0.002±0.007 X: 0.0006±0.002	Pos: < 2 e-21 m (95% confidence) Pit (field): < 7 e-20 rad Yaw (field): < 9 e-21 rad	Expected: 0.72 Measured 0.47±0.03
UIM, almost all 304, without magnets, flags, or BOSEMS, but with blades	Y: 0.002±0.008 Z: 0.02±0.02 X: 0.19±0.02	Pos: < 2 e-21 m Pit (field): < 3 e-19 rad Yaw (field): 8 e-19 rad	Expected: 0.72 Measured: 0.64±0.07
Blade spring from UIM, field along Y: medium axis Z: short axis X: long axis*	Y: 0.014±0.005 Z: 0.00±0.02 X: 0.099±0.003		

Moment induced by magnets

Magnets are placed at the same distance from parts as in quad



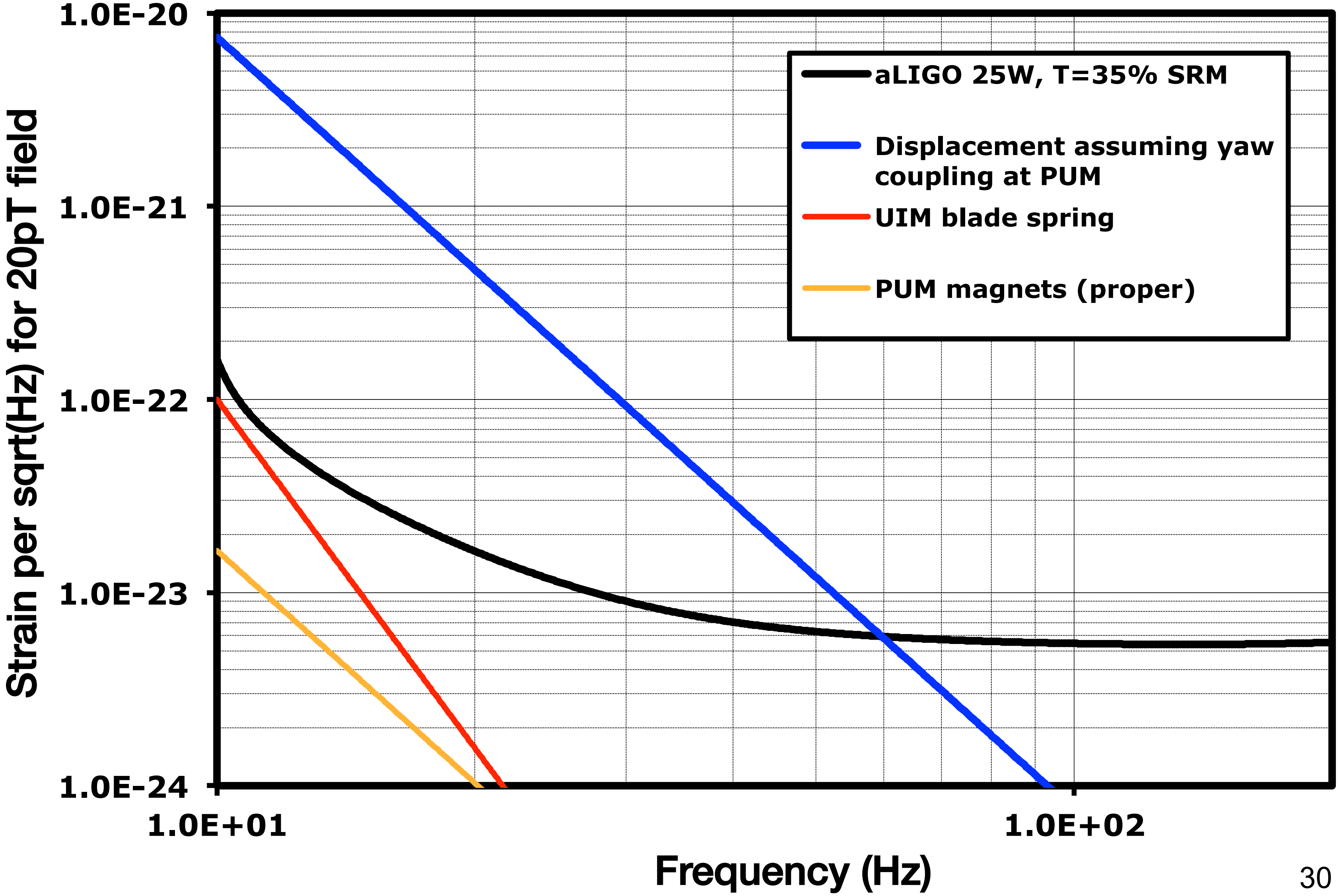
Moment reduced when canceling magnets moved closer together



Magnetization or gradient from nearby permanent magnets

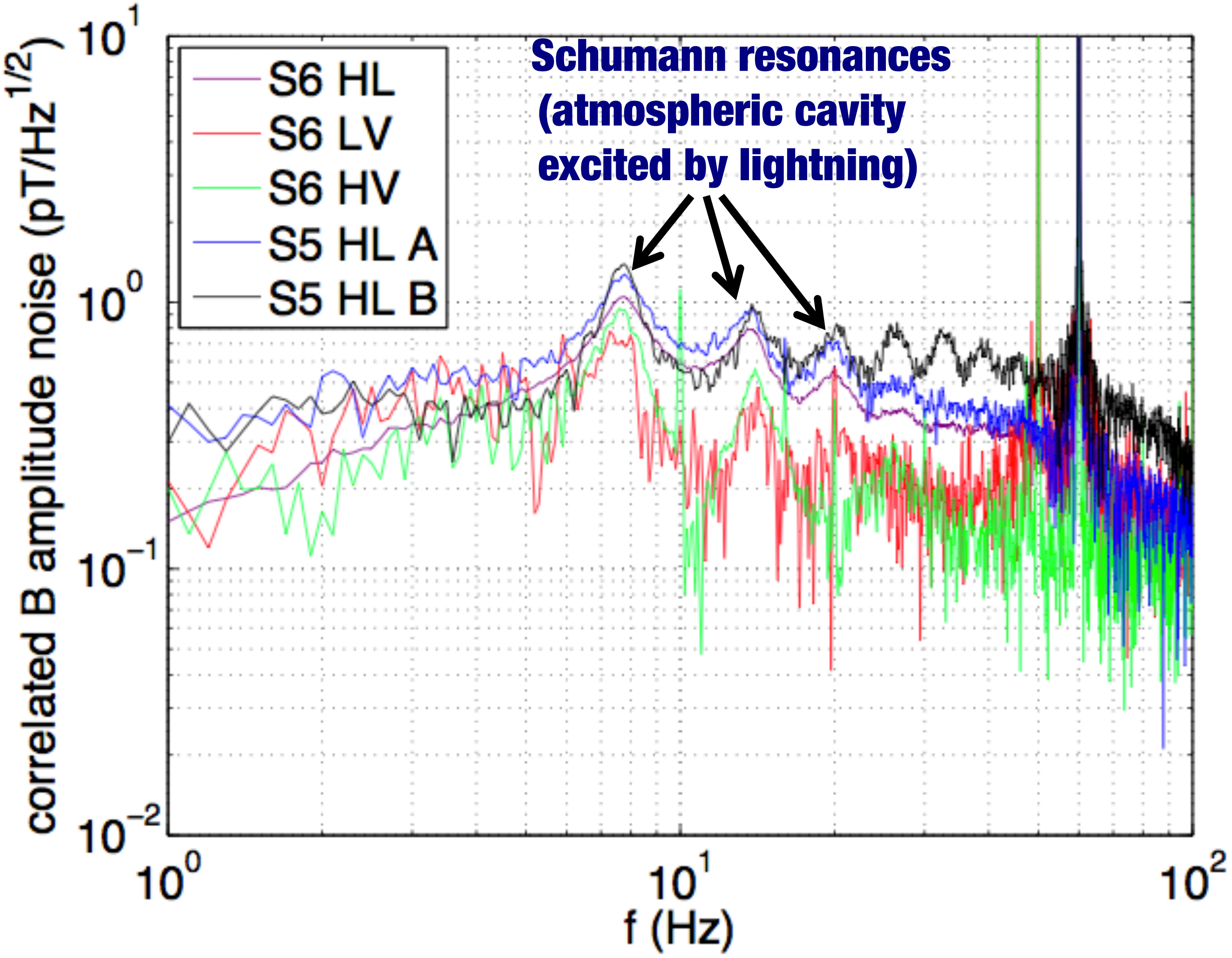
Sample	**Measured magnetic moment** For parts magnetized by nearby permanent magnets (J/T)	**DC magnetization and varying gradients and fields** Estimated test mass motion at 10 Hz from varying ambient gradients (pos) or fields (pit, yaw) assuming 20pT ambient field with B/gradB = 0.06 m. Moment is induced by nearby permanent magnets. (m, rad, rad)	**DC gradients and varying magnetization** Estimated test mass motion at 10 Hz from varying magnetization from 20 pT magnetic field and gradients from permanent magnets (only for reaction chain)
Single blade spring from UIM with 2 magnets from a flag mounted at their relative locations, but only the blade was on moment balance	Y: 0.27±0.06 Z: 0.02+0.1 X: 0.06±0.08	**Pos: 7 e-20 m** Pit (grad): 4.5 e-19 Yaw (grad): 3.0 e-18 Pit (field): < 9 e-19 rad Yaw (field): < 4 e-19 rad	**Pos: 2 e-19 m** Yaw (grad): 2.8e-18 Pit (grad): 1.9e-19 Pit (field): < 4 e-19 rad Yaw (field): < 2 e-18 rad
Single blade spring from UIM with 2 flag magnets as above, but with the two magnets moved until touching each other.	Y: 0.04+0.07 Z: nominal not seen X: nominal not seen	Pos: < 3 e-20 m Pit: nominal not seen Yaw: nominal not seen	Pos: < 8 e-20 m Pit: nominal not seen Yaw: nominal not seen

Summary of worst coupling



Global correlated magnetic noise

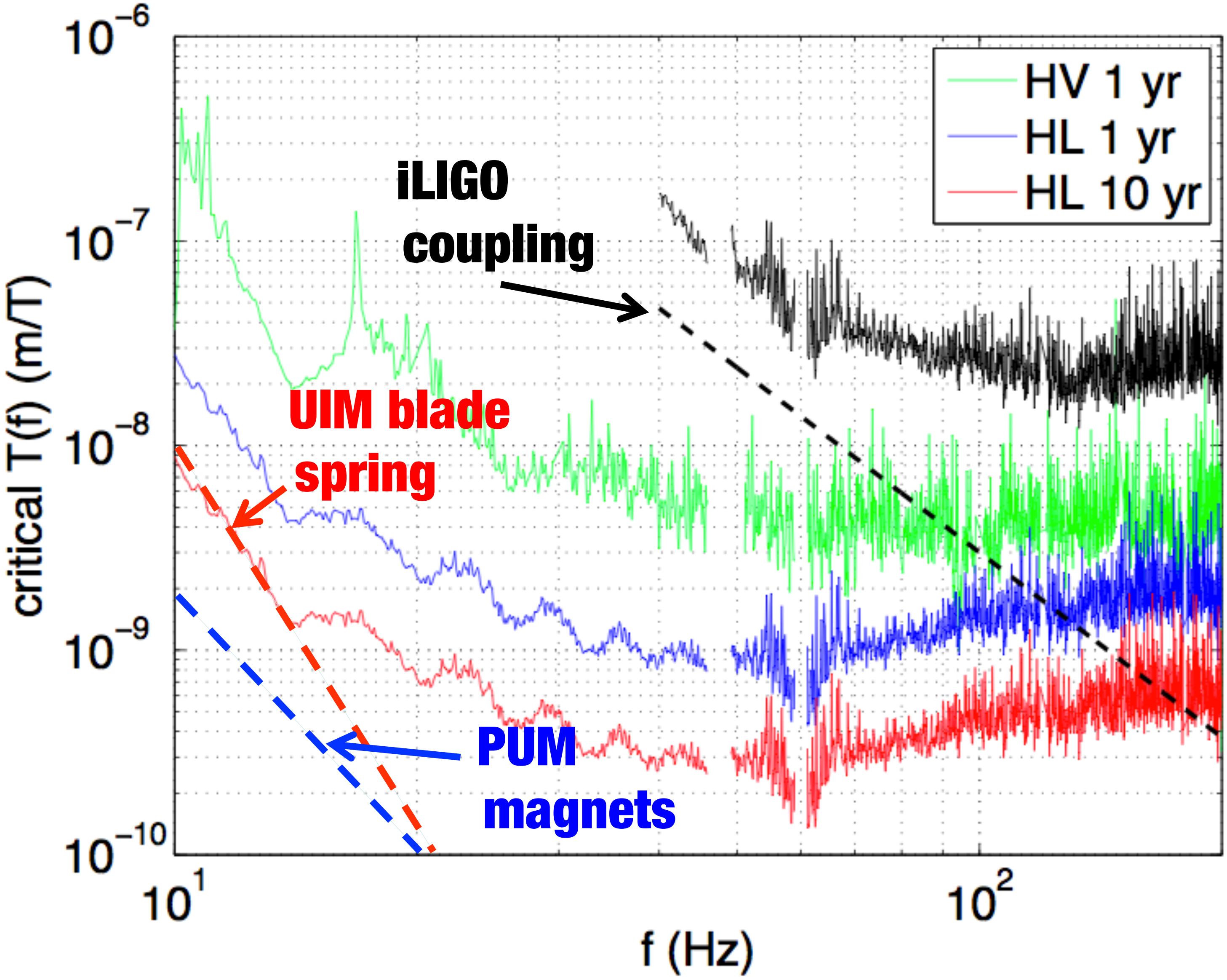
Magnetic coupling is also important for stochastic GW analysis



Schumann resonances (atmospheric cavity excited by lightning)

From paper by Eric Thrane, Nelson Christianson, Robert Schofield

Critical coupling



iLIGO coupling

UIM blade spring

PUM magnets

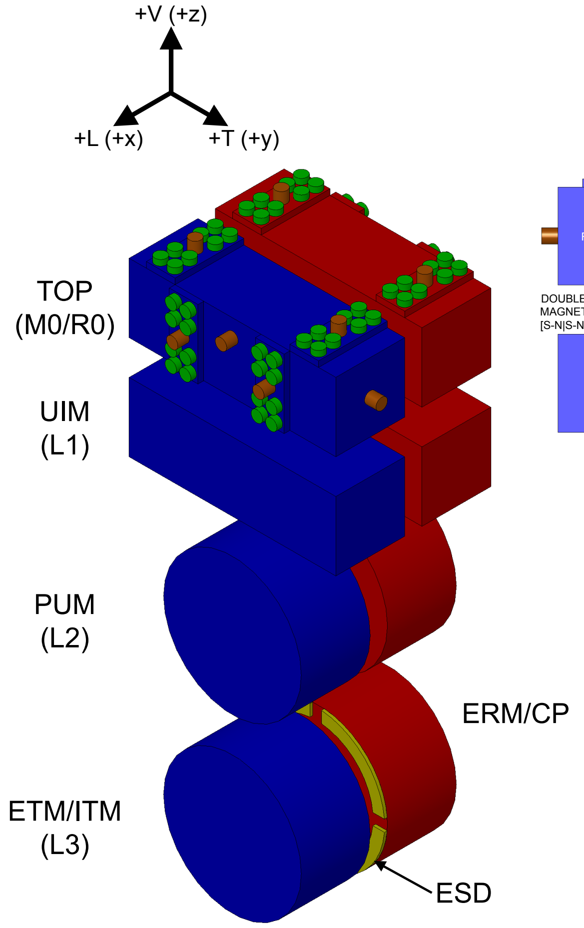
Summary of most important results

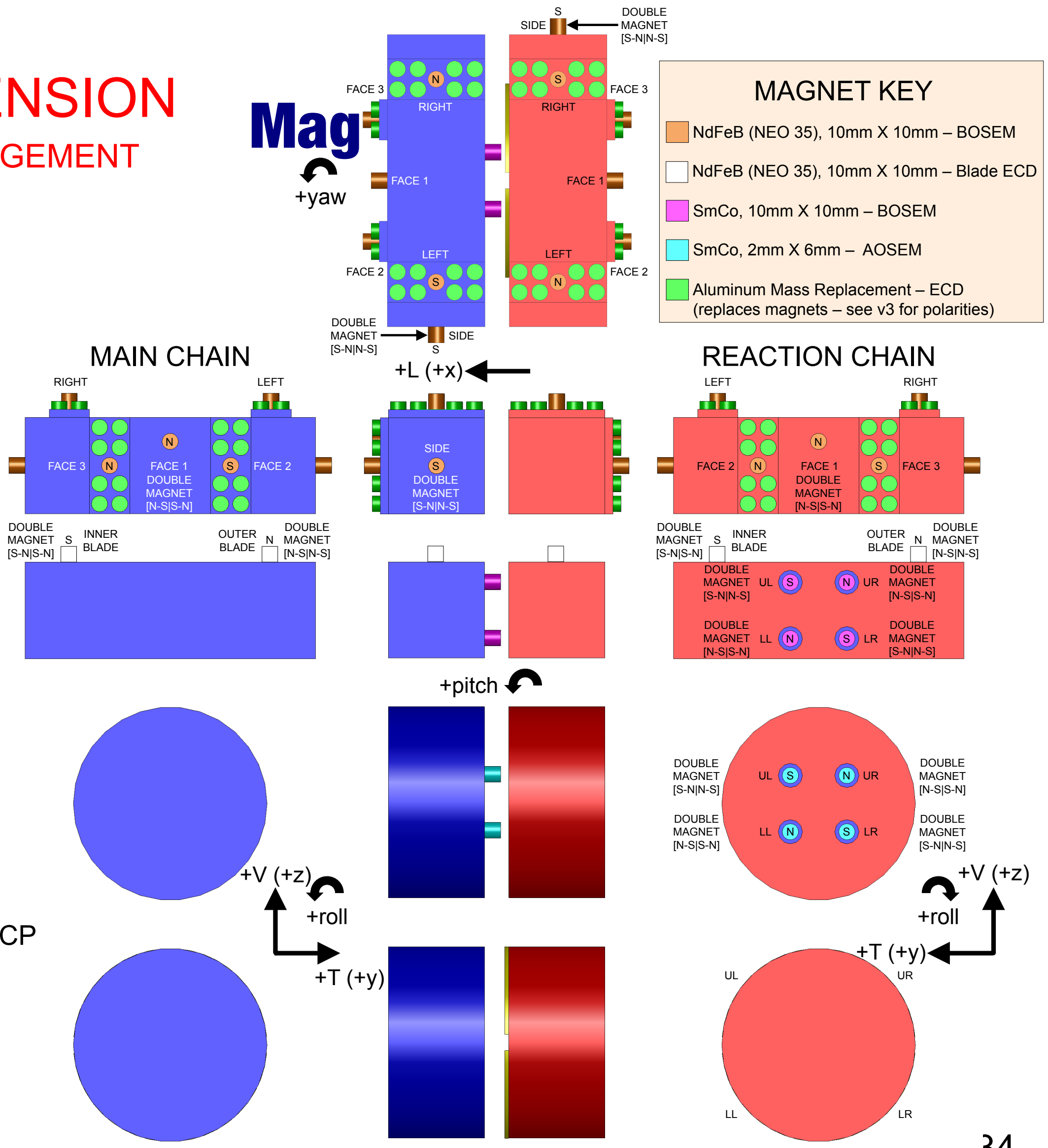
- **Have found nothing that can explain yaw coupling from post ECD**
- **If we ignore yaw, removal of ECD magnets reduced coupling by a factor of about 4**
- **Pitch coupling could be explained by 1 or 2 reversed UIM or PUM magnets but not by coupling to paramagnetic materials**
- **The worst estimated coupling is to the UIM steel blade springs, not the 304 steel on the UIM and PUMre (2e-19/sqrt(Hz) @ 10 Hz, about 10 x spec. and right at the aLIGO noise floor at 10 Hz)**
- **The worst predicted coupling to the blade springs is, for reaction chain, varying ambient magnetization in gradients from permanent magnets, followed by magnetization from permanent magnets in varying ambient gradients**
- **These two mechanisms could be reduced by moving the cancelling magnets closer**
- **This coupling is about ten times worse than Stochastic desires**
- **Magnetic coupling to electronics and cables has not yet been tested**

E1000617-v5
DEREK BRIDGES

QUAD SUSPENSION

CONTROLS ARRANGEMENT





MAGNET KEY

- 🟧 NdFeB (NEO 35), 10mm X 10mm – BOSEM
- ☐ NdFeB (NEO 35), 10mm X 10mm – Blade ECD
- 🟪 SmCo, 10mm X 10mm – BOSEM
- 🟦 SmCo, 2mm X 6mm – AOSEM
- 🟩 Aluminum Mass Replacement – ECD (replaces magnets – see v3 for polarities)