Modeling Magnetic Coupling to Suspensions

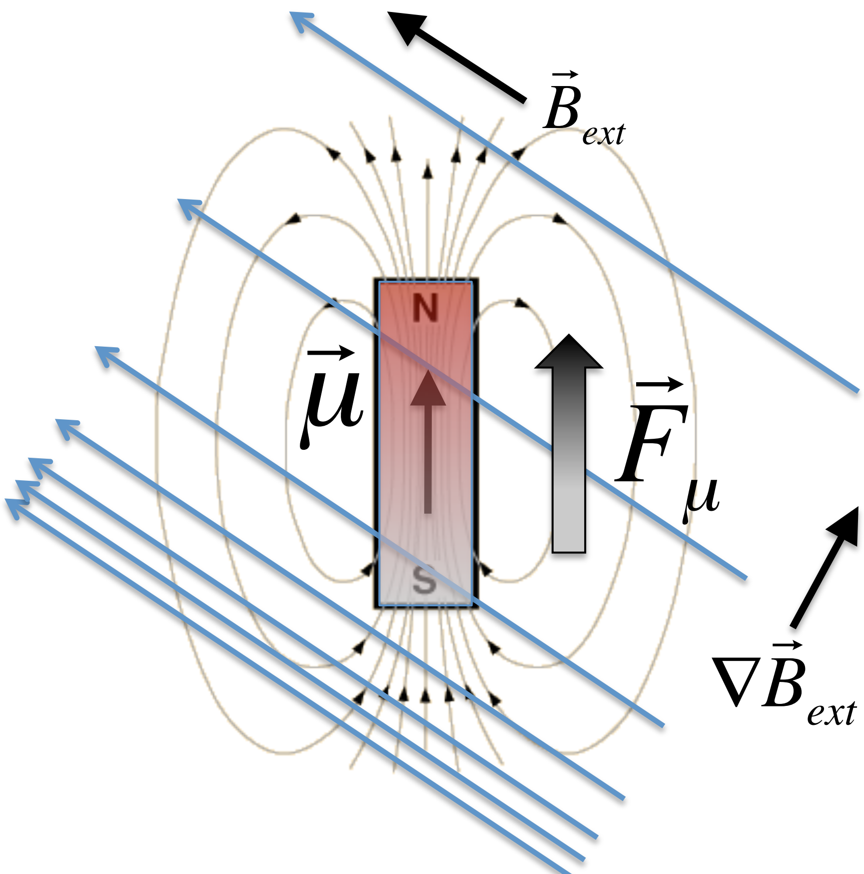
Part 1: The Physics and Designed Mitigation

G1200524-v2

J. Kissel

Physics 202
Freshman Year Magnetism

In the presence of an external static (independent of time/frequency) **Magnet Field**, the force felt on a **Magnet** is:

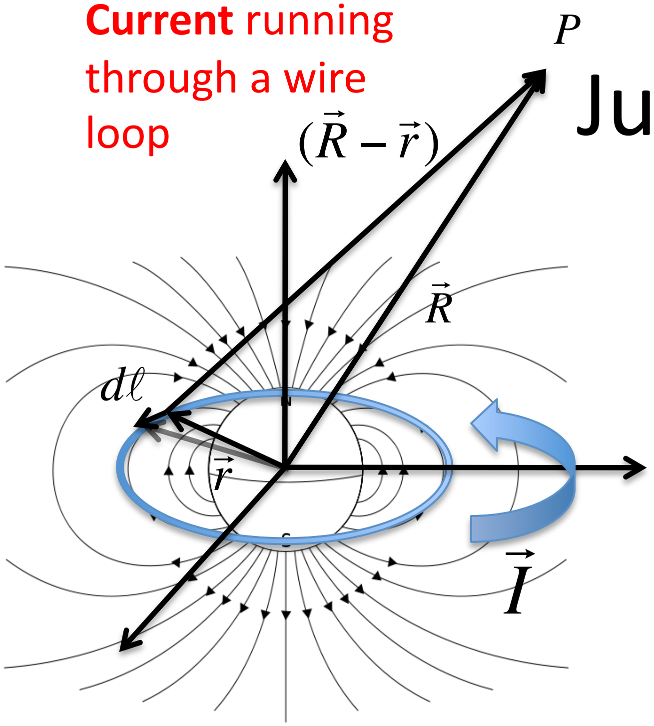


$$\vec{F}_{\mu} = (\vec{\mu} \bullet \vec{\nabla})\vec{B}_{ext}$$

- $\vec{\mu}$: Magnetic Dipole Moment
- $\bullet$: In the same direction as
- $\vec{\nabla}$: Gradient (change in slope of)
- $\vec{B}_{ext}$: External Magnetic Field

Physics 402
Junior Year Magnetism

Current running through a wire loop



The Magnetic **Field** is a function of the Magnetic **Vector Potential**

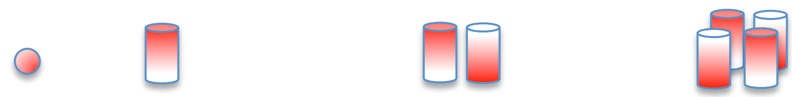
$$\vec{B} = \vec{\nabla} \times \vec{A}$$

In general, the Magnetic **Vector Potential** is defined by integrating over a local **Current Density** as observed from a **Point** some **Distance** away

$$\vec{A}(\vec{R}) = \frac{\mu_0}{4\pi} I \oint \frac{1}{|\vec{R}-\vec{r}|} d\vec{\ell}$$

If sufficiently far away, you can make the **Multipole Approximation**

$$r << R$$



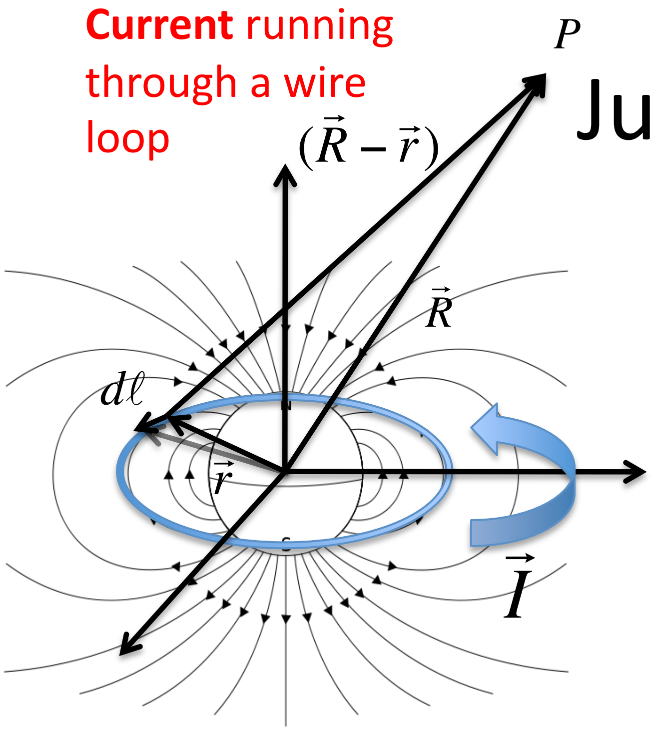
$$\frac{1}{|\vec{R}-\vec{r}|} \approx \frac{1}{R} + \frac{\vec{R}\bullet\vec{r}}{R^3} + \frac{3\,(\vec{R}\bullet\vec{r})^2 - R^2 r^2}{R^5} + \dots$$

Monopole Dipole Quadrapole Octopole

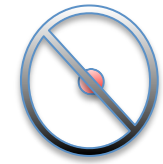
with which you can see what terms dominate the **Potential**

$$\propto \frac{1}{R} + \frac{r}{R^2} + \frac{r^2}{R^3} + \frac{r^3}{R^4} + \dots$$

Physics 402
Junior Year Magnetism

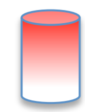


But, Maxwell says there're no magnetic monopoles $\vec{\nabla}\bullet\vec{B}=0$



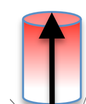
So the dominant term left is the **Dipole**

$$\vec{A}_{DIPOLE}(\vec{R}) = \frac{\mu_0}{4\pi}\left[\frac{(\vec{\mu}\times\vec{R})}{R^3}\right] \propto \frac{r_\mu^2}{R^2}$$



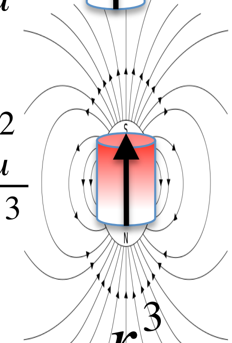
Where we've defined the **magnetic dipole moment**

$$\vec{\mu} \equiv I\oint(\hat{R}\bullet\vec{r})d\ell = I\int d\vec{a} = I\,\vec{A} \propto r_\mu^2$$



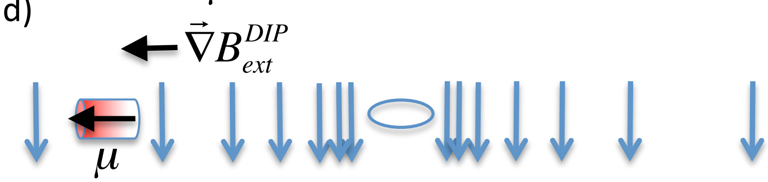
Which means (after "some math") the **Magnetic Dipole Field** is

$$\vec{B}_{DIP}(\vec{R}) = \vec{\nabla}\times\vec{A}_{DIP} = \frac{\mu_0}{4\pi}\frac{1}{R^3}\left[3(\vec{\mu}\bullet\hat{R})\hat{R}-\vec{\mu}\right] \propto \frac{1}{R}\cdot\frac{r_\mu^2}{R^2} \propto \frac{r_\mu^2}{R^3}$$



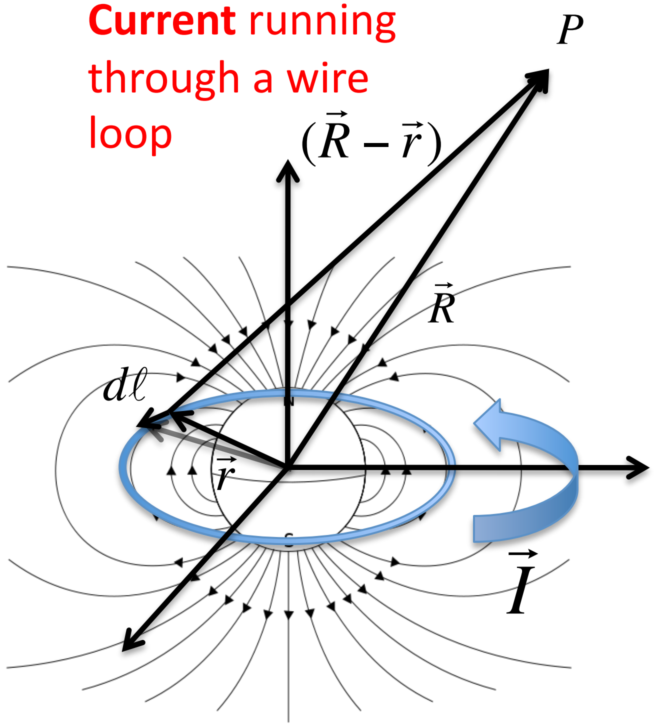
So, an **External Field**, assuming it's also a dipole, acting on a **dipole moment** feels a **Force**
(where the **Gradient** is over the coordinates of the moment *not* the external field)

$$\vec{F}_\mu^{DIP} = (\vec{\mu}\bullet\vec{\nabla})\vec{B}_{ext}^{DIP} \propto \left(r_\mu^2\cdot\frac{1}{r_\nabla}\right)\frac{r_{ext}^2}{R^3} \propto \frac{r^3}{R^3}$$



assume $r_{ext} \approx r_\nabla \approx r_\mu = r << R$

Current running through a wire loop



Physics 502
Senior Magnetism

Thus far we've assumed a static field, created by a constant current. What if that current is a function of time?

$$\vec{I}(t) = \vec{I}_0 \cos\left[\omega\left(t - \tfrac{|\vec{R}-\vec{r}|}{c}\right)\right]$$

Electromagnetic waves!

$$\vec{A}(t) = \frac{\mu_0}{4\pi} I_0 \oint \frac{\cos\left[\omega\left(t - \frac{|\vec{R}-\vec{r}|}{c}\right)\right]}{|\vec{R}-\vec{r}|} d\vec{\ell}$$

$$\vec{B}(t) = \vec{\nabla} \times \vec{A}(t)$$

$$\vec{E}(t) = \frac{\partial \vec{A}(t)}{\partial t}$$

After "some math," the dominate **dipole** field (in spherical coordinates) [Cowan, 1968]

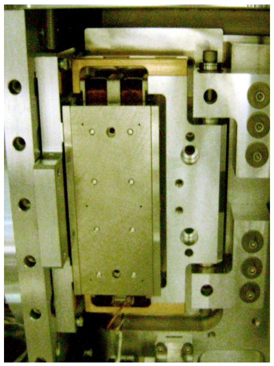
$$B_r = \frac{2\mu_0 A\cos\theta}{4\pi} I_0 \left[\frac{1}{R^3}\cos[\omega(t-R/c)] - \frac{\omega}{R^2 c}\sin[\omega(t-R/c)]\right]$$

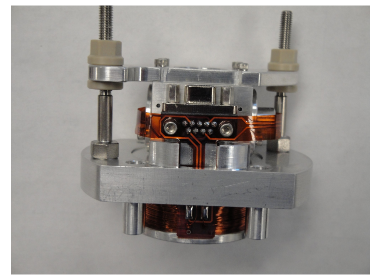
$$B_\theta = \frac{\mu_0 A\sin\theta}{4\pi} I_0 \left[\left(\frac{1}{R^3} - \frac{\omega^2}{rc^2}\right)\cos[\omega(t-R/c)] - \frac{\omega}{R^2 c}\sin[\omega(t-R/c)]\right]$$

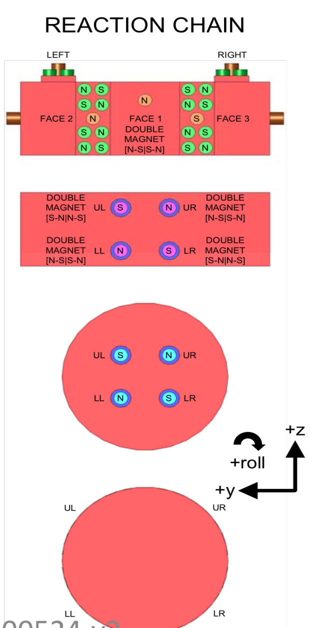
$$E_\phi = \frac{\mu_0 A\sin\theta}{4\pi} I_0 \left[\frac{\omega^2}{Rc}\cos[\omega(t-R/c)] + \frac{\omega^2}{R}\sin[\omega(t-R/c)]\right]$$

Physics 502
LIGO Magnetism

We have time dependent **External Fields** all over!





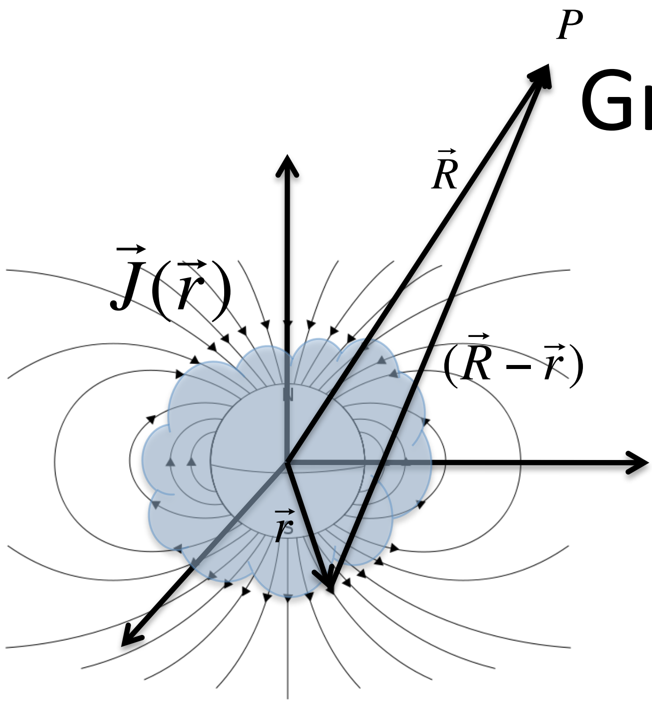


And **magnets** all over for local electromagnetic control!

How are we not screwed?

We arrange the **magnets** to form higher order **Multipoles…**

Physics 702
Graduate Magnetism

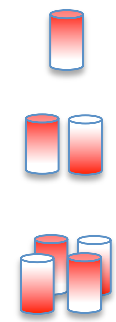


Take an arbitrary distribution of **current density** over some **volume**

$$\vec{A} = \frac{\mu_0}{4\pi}\int_V \frac{\vec{J}(\vec{r})}{|\vec{R}-\vec{r}|}dv$$

but now we **keep** take the multipole expansion of the potential out past the dipole term…

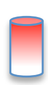
$$A_i = \frac{\mu_0}{4\pi}\left[\begin{array}{l} \frac{R_j}{R^2}\int_V r_j J_i dv + \\ \frac{3R_jR_k - R^2\delta_{jk}}{2R^5}\int_V r_j r_k J_i dv + \\ \frac{5R_jR_kR_\ell - R^2(R_j\delta_{k\ell} + R_k\delta_{\ell j} + R_\ell\delta_{jk})}{2R^7}\int_V r_j r_k r_\ell J_i dv + \\ \ldots \end{array}\right]$$

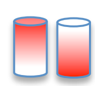


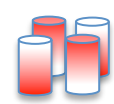
Then we can define the next several **multipole moments**

$$\mu_i \equiv \frac{1}{2}\int_V r_j J_i dv \qquad \mu_{ij} \equiv \frac{2}{3}\int_V r_j r_k J_i dv \qquad \mu_{ijk} \equiv \frac{2}{5}\int_V r_j r_k r_\ell J_i dv$$

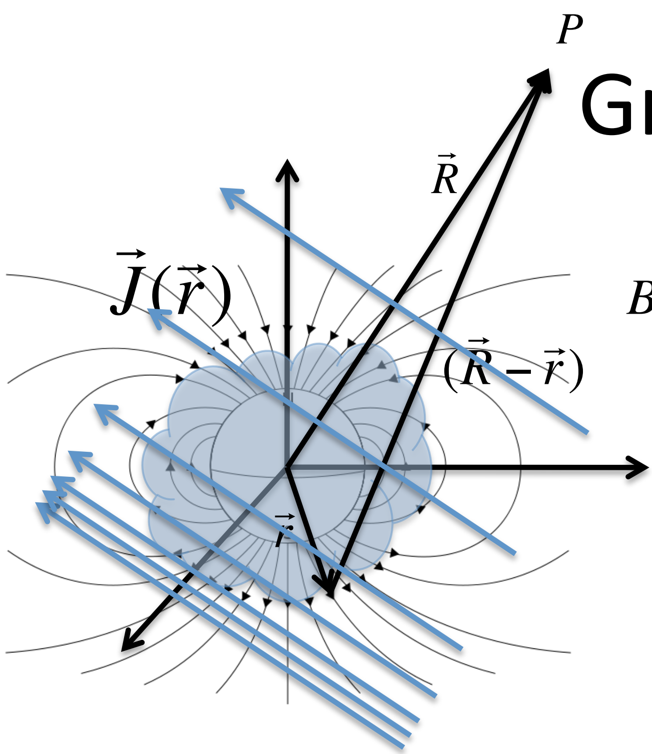
$$\propto r^2 \qquad \propto r^3 \qquad \propto r^4$$


dipole


quadrapole


octapole

Physics 702
Graduate Magnetism



In the presense of an **Slowly Varying External Field**

$$B_k(\vec{R}) = B_k^{(0)} + (\nabla_\ell B_k) r_\ell + \frac{1}{2}(\nabla_m \nabla_\ell B_k) r_\ell r_m + \frac{1}{6}(\nabla_m \nabla_\ell B_k) r_\ell r_m + \ldots$$

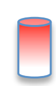
"it can be shown" that the Force on the static **current distribution** is

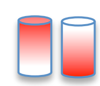
$$F_i = \mu_j \nabla_j B_i + \frac{1}{2}\mu_{jk} \nabla_k \nabla_j B_i + \frac{1}{6}\mu_{jk\ell} \nabla_\ell \nabla_k \nabla_j B_i + ..$$

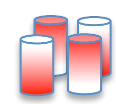
$$\propto r_\mu^2 \frac{1}{r_\nabla} \frac{r_{ext}^2}{R^3} + \quad r_\mu^3 \frac{1}{r_\nabla^2} \frac{r_{ext}^3}{R^4} \quad + \quad r_\mu^4 \frac{1}{r_\nabla^3} \frac{r_{ext}^4}{R^5} \quad + \ldots$$

assume $r_{ext} \approx r_\nabla \approx r_\mu = r << R$

$$\propto \quad \frac{r^3}{R^3} \quad + \quad \frac{r^4}{R^4} \quad + \quad \frac{r^5}{R^5} \quad + \ldots$$


dipole


quadrapole

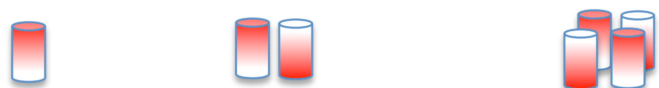

octapole

Up to this point, we've worked to get to the ultra general case where we assume the **current density** is arbitrarily complicated which, by itself, has all of these **moments** that interact with the **external field**. Let's get back to **LIGO**.

Physics 702
LIGO Magnetism

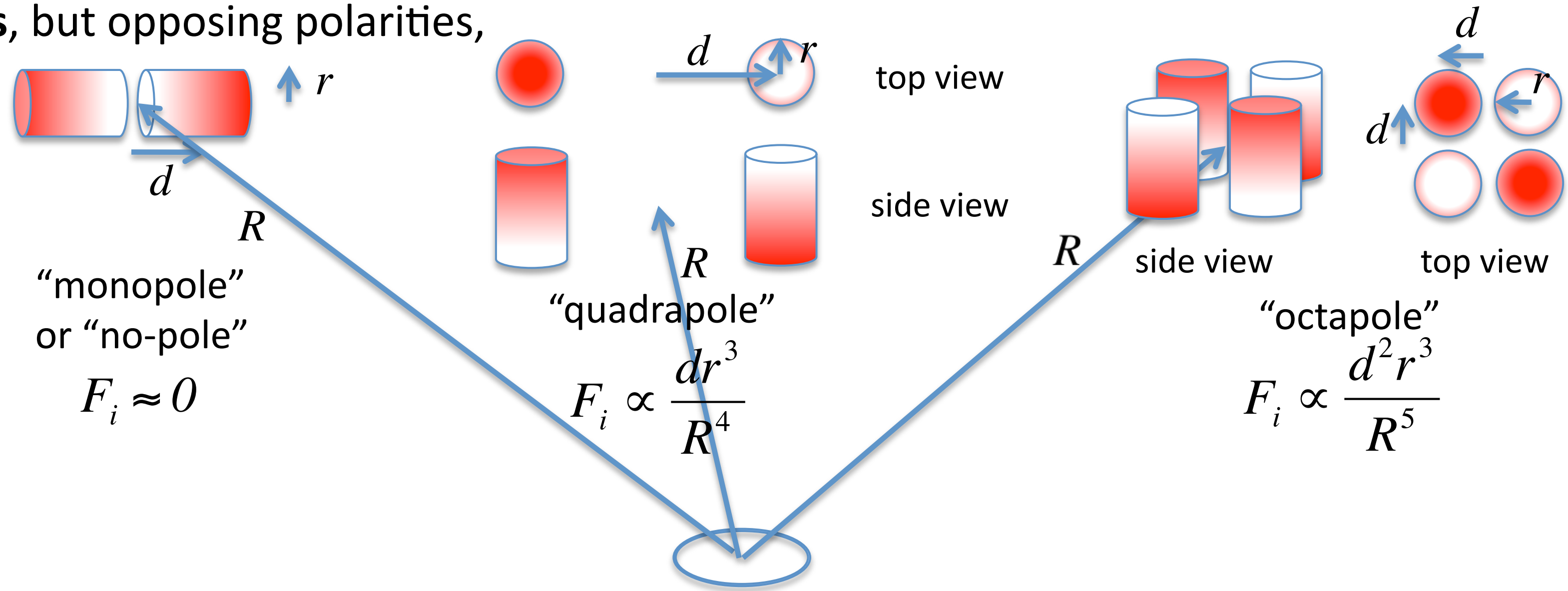
We are free to set up the **current density** (i.e. the **magnets**) exactly how we want it, and create **ideal multipole moments** with our magnets, that, in the far field (r<<R), behave like higher order **moments** only, and therefore couple less to external fields (the force falls off with distance faster)

$$F_i \propto \frac{r^3}{R^3} + \frac{r^4}{R^4} + \frac{r^5}{R^5} + \ldots$$



dipole quadrapole octapole

Take various combinations of **ideal dipoles** with identical **dimensions** and **magnetic moments**, but opposing polarities,



"monopole" or "no-pole"

$$\frac{d}{R} \approx \frac{r}{R} << 1 \qquad F_i \approx 0$$

"quadrapole"

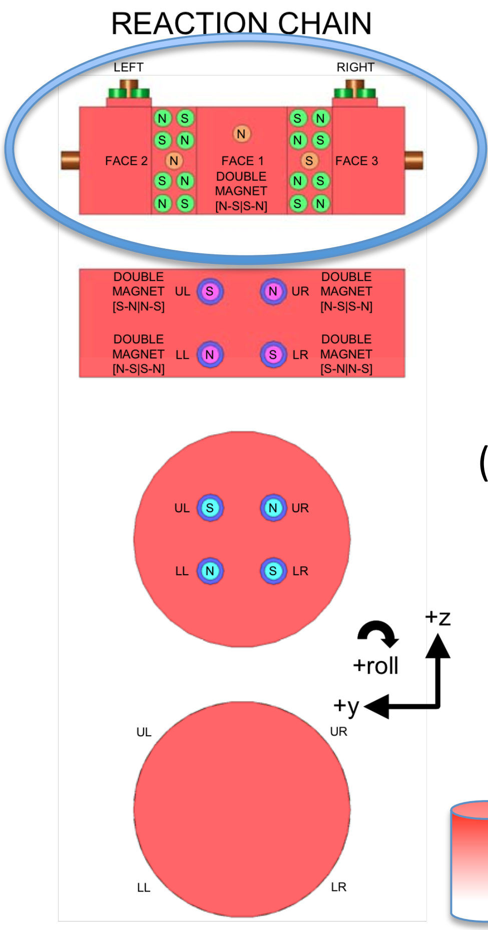
$$F_i \propto \frac{dr^3}{R^4}$$

"octapole"

$$F_i \propto \frac{d^2 r^3}{R^5}$$

Physics 502
LIGO Magnetism

Look at a **QUAD Top Mass**, for example…

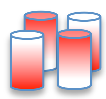


$r = 1\ cm$

$d_{monopoles} \approx 1\ cm$

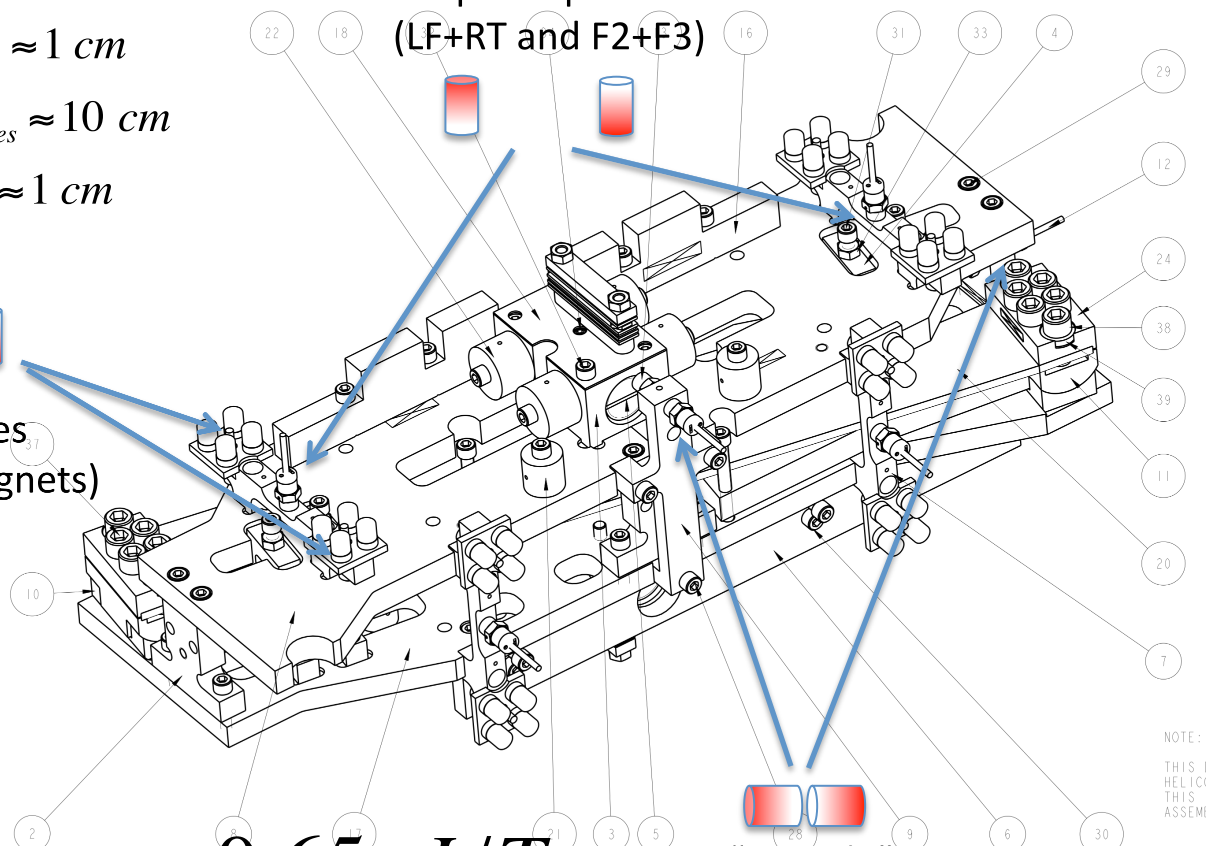
$d_{quadrapoles} \approx 10\ cm$

$d_{octapoles} \approx 1\ cm$



octapoles
(All ECD Magnets)

quadrapoles
(LF+RT and F2+F3)



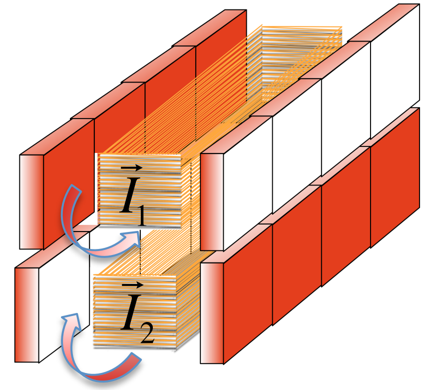
"no-pole"
(F1 and SD)

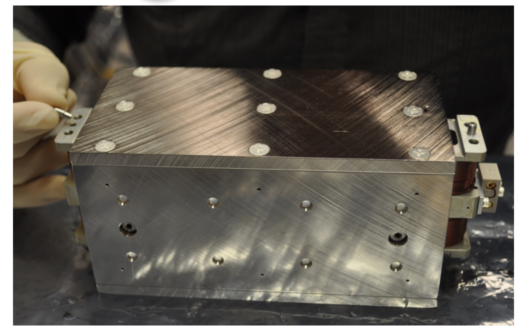
$$\mu_{NdFeB} \cong 0.65\ \ J/T$$
$10x10mm$

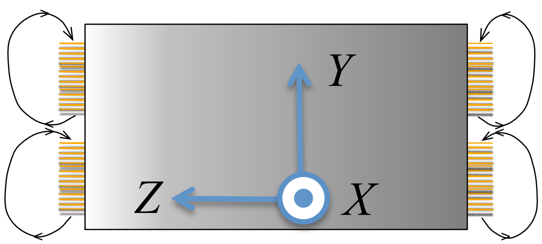
Physics 702
LIGO Magnetism

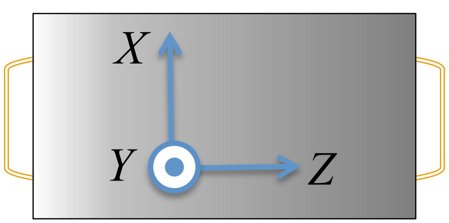
Or an **ISI "Coarse" Actuator** (ST1 on HAM and BSC), for example…

There are two counter-wound coils to create a quadrapole
Also, they're shielded in the "X" and "Y" direction with iron housing

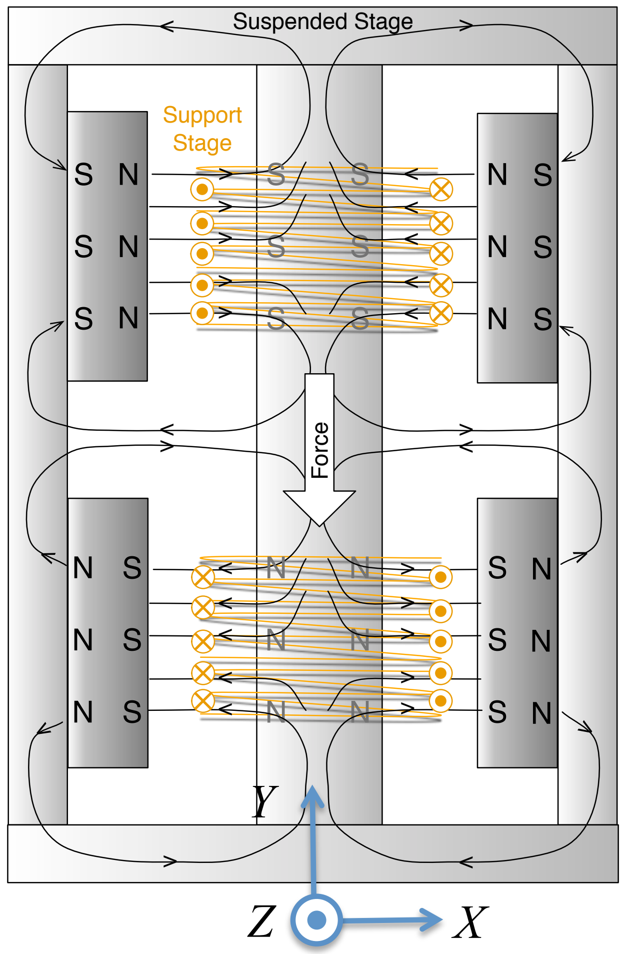








Magnetic flux is confined to the ferromagnetic material



Sect. 5.13 Effect of a Circular Hole in a Perfectly Conducting Plane 203

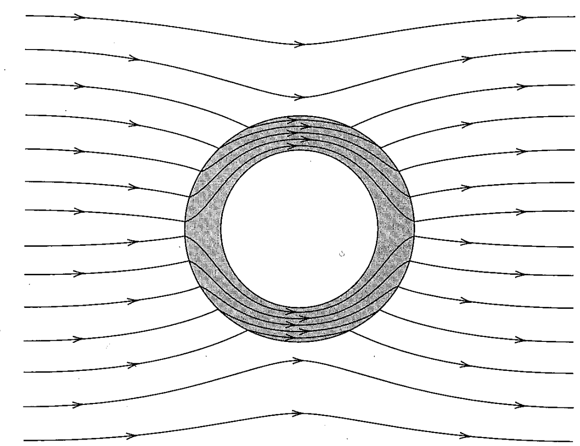


Figure 5.14 Shielding effect of a shell of highly permeable material.

Jackson has a section on magnetic shielding if you're interested…

Modeling Magnetic Coupling to Suspensions

Part 2: The Real World and a "Simple" Model

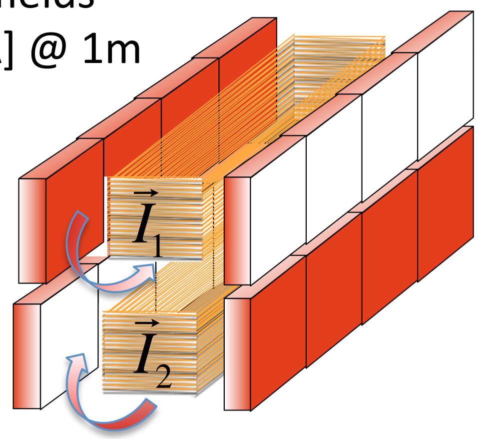
G1200524-v2

J. Kissel

Physics 2012
The Stuff that isn't in Textbooks

But, as you might guess the real world is not so "pretty."

ISI Actuators have stray dipole fields ~10^{-7} [T/A] @ 1m

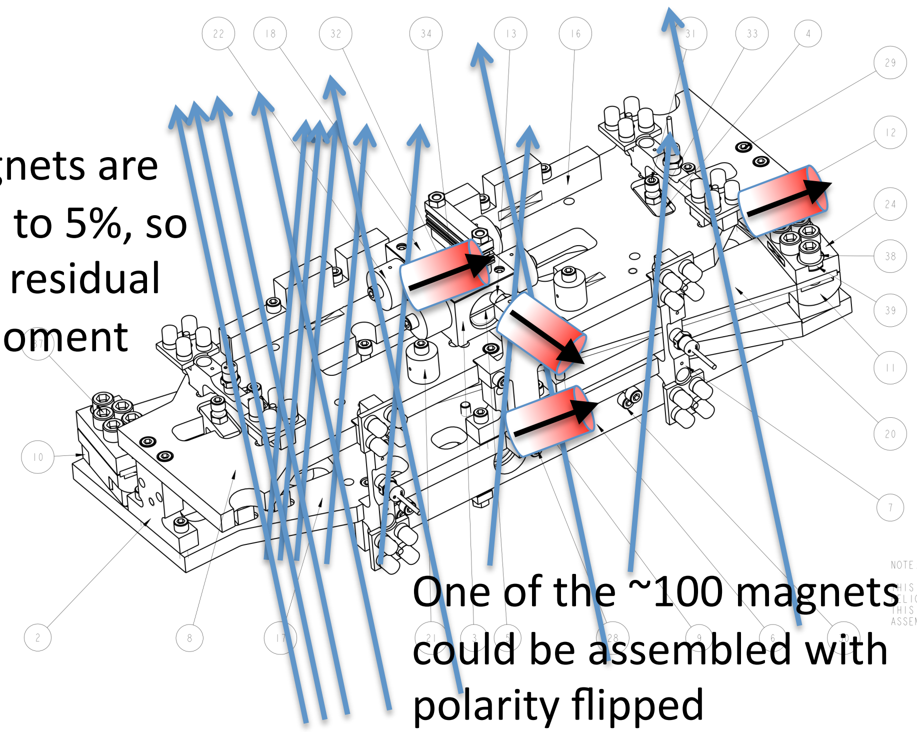


Power lines spew 60Hz fields at ~10^{-7} T RMS

Sources

SUS Magnets are matched to 5%, so there's a residual dipole moment

Some cancelation pairs are ~10cm appart, and GradB changes over that scale

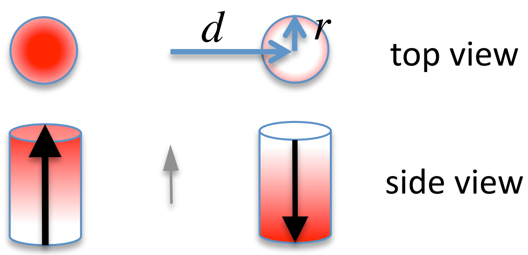


One of the ~100 magnets could be assembled with polarity flipped

Sink

Physics 2012
The Stuff that isn't in Textbooks

Take the "quadrupole" that we mentioned earlier:



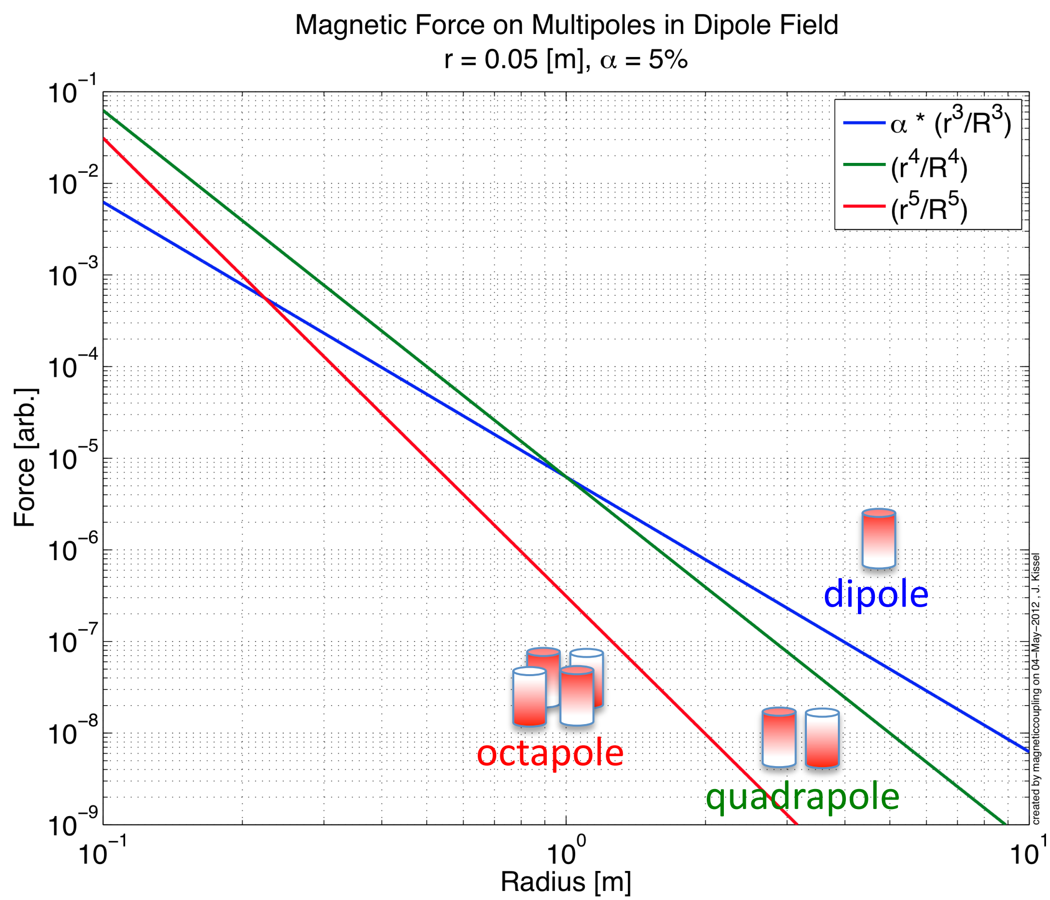
"quadrapole"

If the **magnets** are mismatched by α, there is a **residual dipole moment,** μ' equivalent to one of the individual dipole, reduced by the mismatch,

$$\mu' = (1+\alpha)\mu - \mu = \alpha\mu$$

and the force experienced in a external dipole now goes as

$$F_i \propto \alpha \frac{r^3}{R^3} + \frac{r^4}{R^4} + \ldots$$



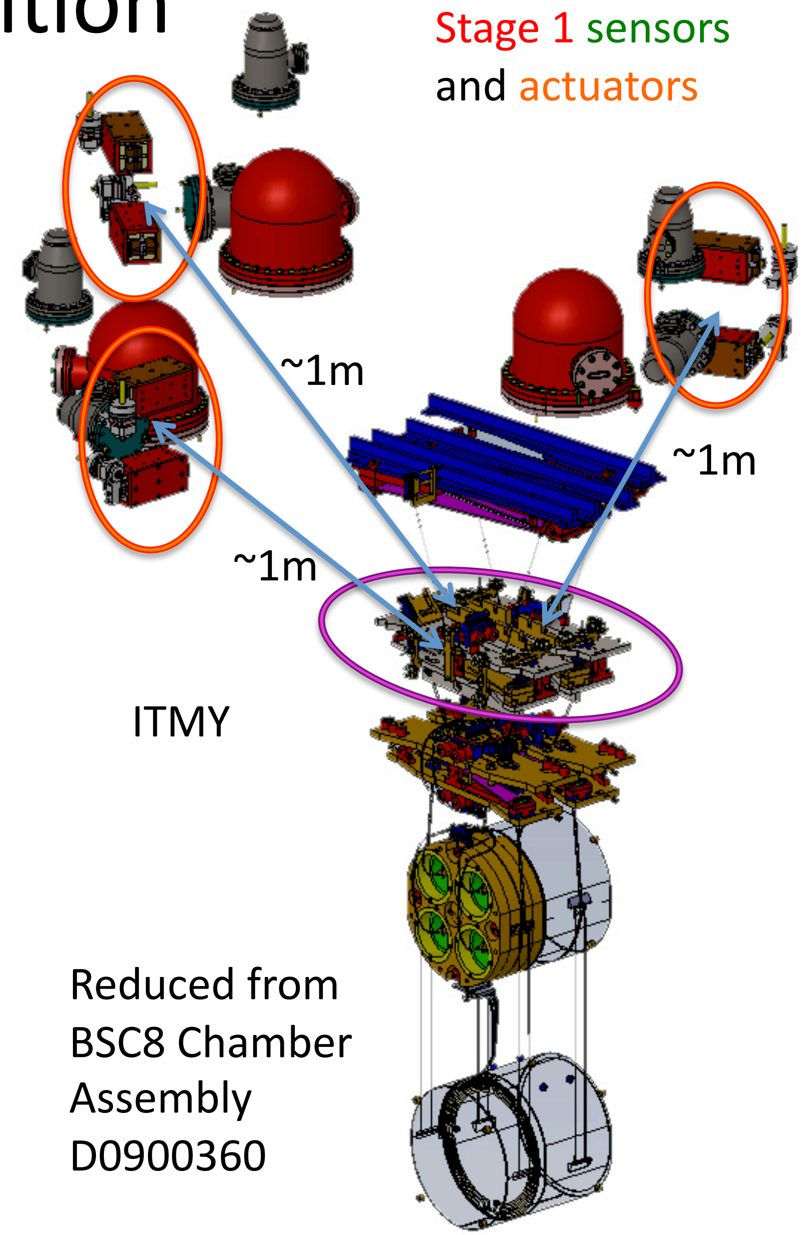
and the (reduced) **dipole term dominates** again in the **far field**

A “Simple” Model
The Preposition

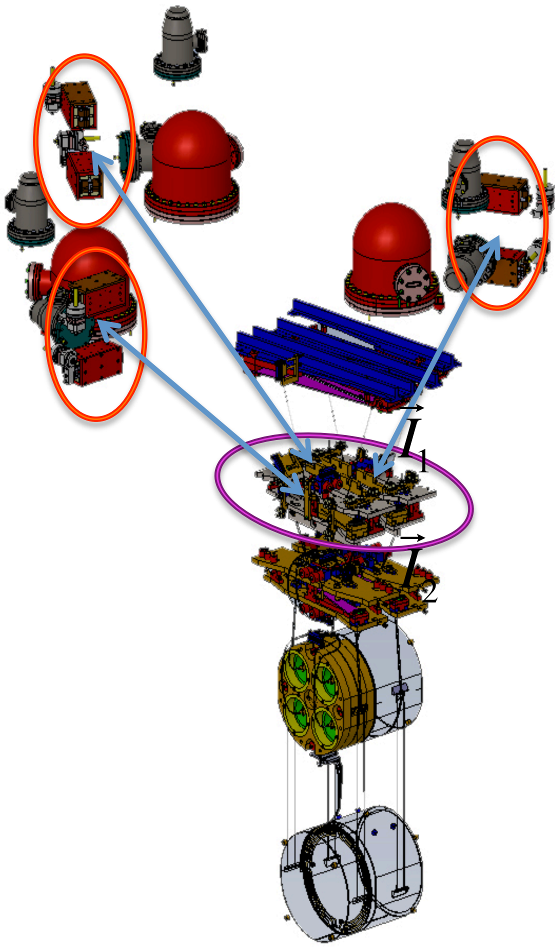
Six, BSC-ISI Stage 1 Actuators are roughly 1m away from the TOP mass(es) of a QUAD

Assuming the ISI actuators generate **stray fields** when working to isolate ST1,

How much can they **drive** before the **magnetic force** on the **residual dipole moment** of the **TOP mass(es)** shorts the mechanical & controlled isolation from ST2 and the TOP stage suspension?



A “Simple” Model
The History



Requirements:

−From **T010007**, 4.2.7 (Barton, Robertson, Fritschel, Shoemaker, Willems)
“… We require that [technical noise] be … 10% [the] amplitude of … pendulum thermal noise. Sources include … ambient magnetic field fluctuations at the magnetic actuators… .”

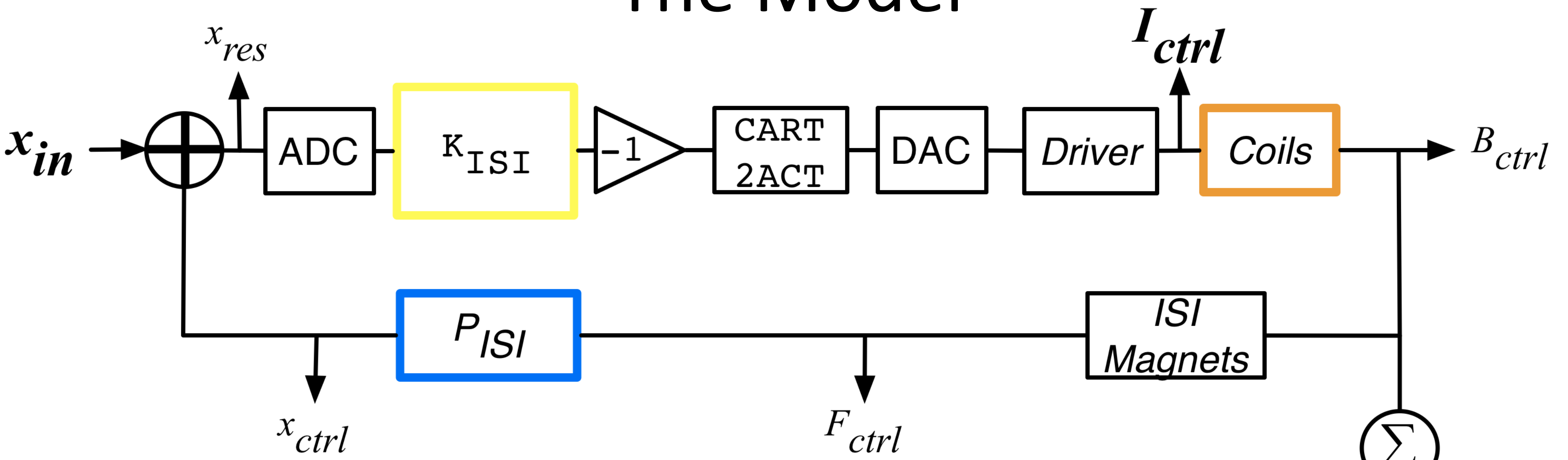
−From **E050159**, Sect. 1.1.4.5 (D. Coyne)
“… max magnetic field and gradient, at … 10 cm below the optics table, due to SEI Actuators … shall be < 10 [pT/rtHz] and 20 [pT.m^{-1}/rtHz] at 10 Hz, varying as 1/f.”

Previous work:

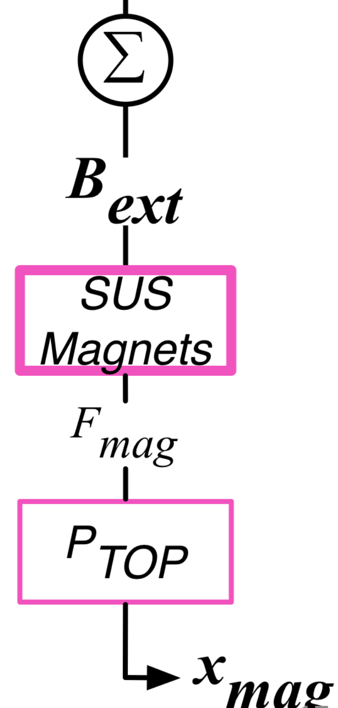
From **T050105** (K. Strain)

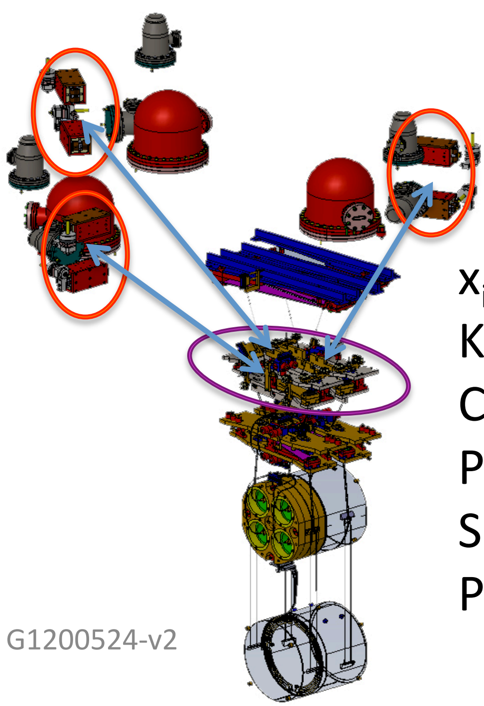
−Used requirements from **E050159** for input field
−Assumed (former baseline design of) ECD magnets on tablecloth
−Only estimated at 10 Hz
−Was before final BSC-ISI design
−Assumed Top mass was 0.2 m away
−Used VtoV * 0.001 Top to Test TF
−“Largest allowable dipole moment is 1 [A.m^2]”

A “Simple” Model
The Model



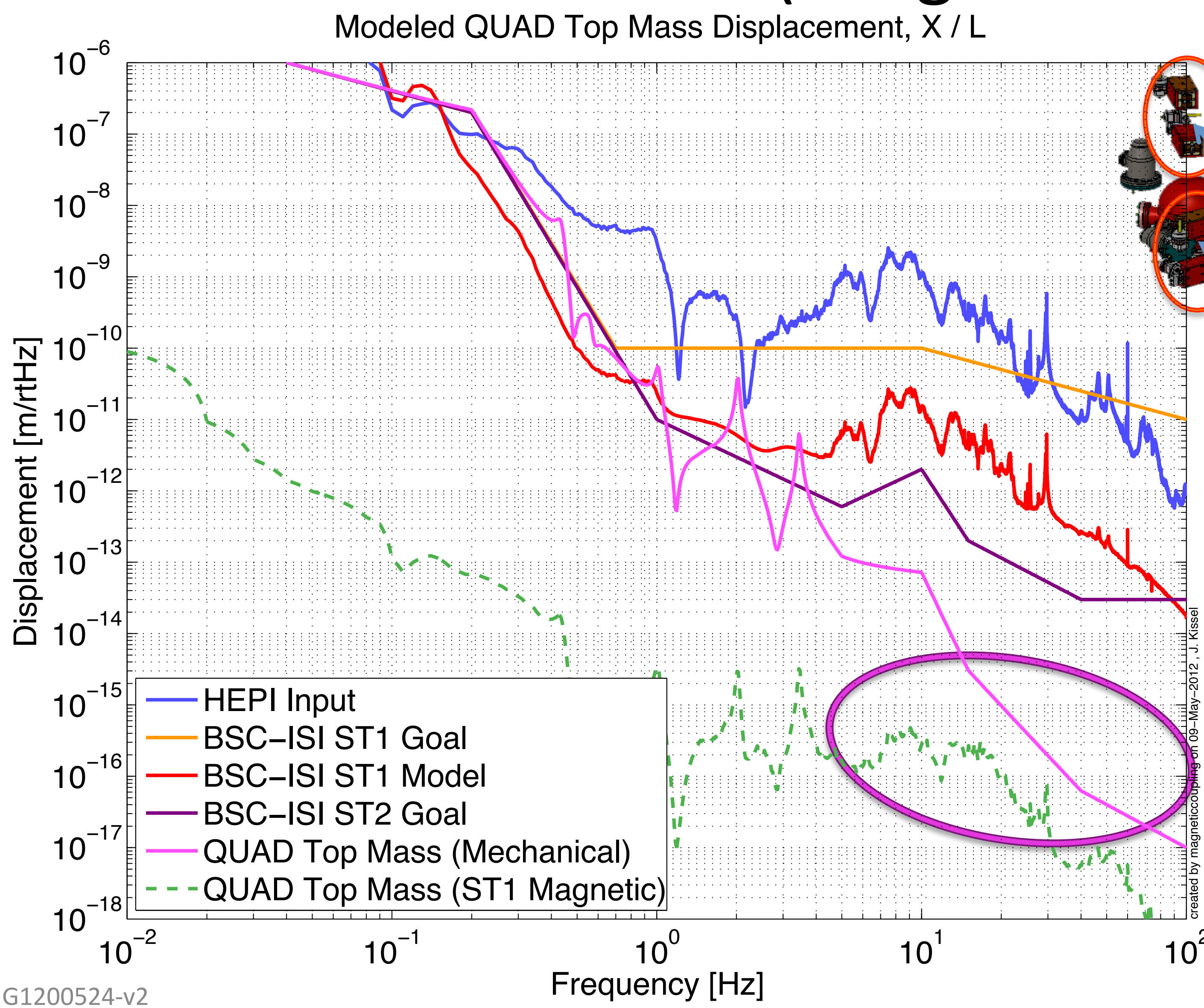
See **Part 3** for details of each component, but:

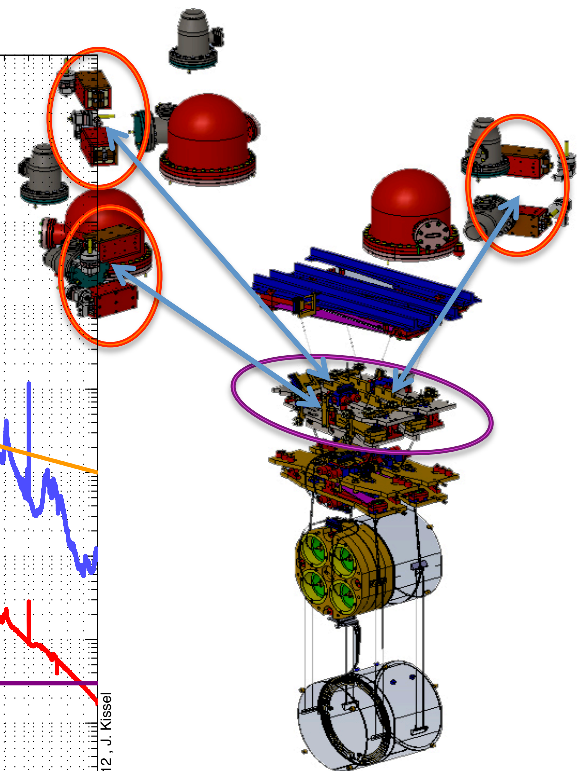




x_{in} [m] – eLIGO HEPI Data, T0900312 (Waldman)
K_{ISI} [ct/m] – Designed for this model (Me)
Coils [T/A] – From old Coarse Actuator (Rich)
P_{ISI} [m/N] – From BSC8 ISI in SeiSVN (Vincent, Me)
SUS Magnets [J/T] – From T1100215 (Rai)
P_{TOP} [m/N]– Production QUAD Model (Barton, Me)

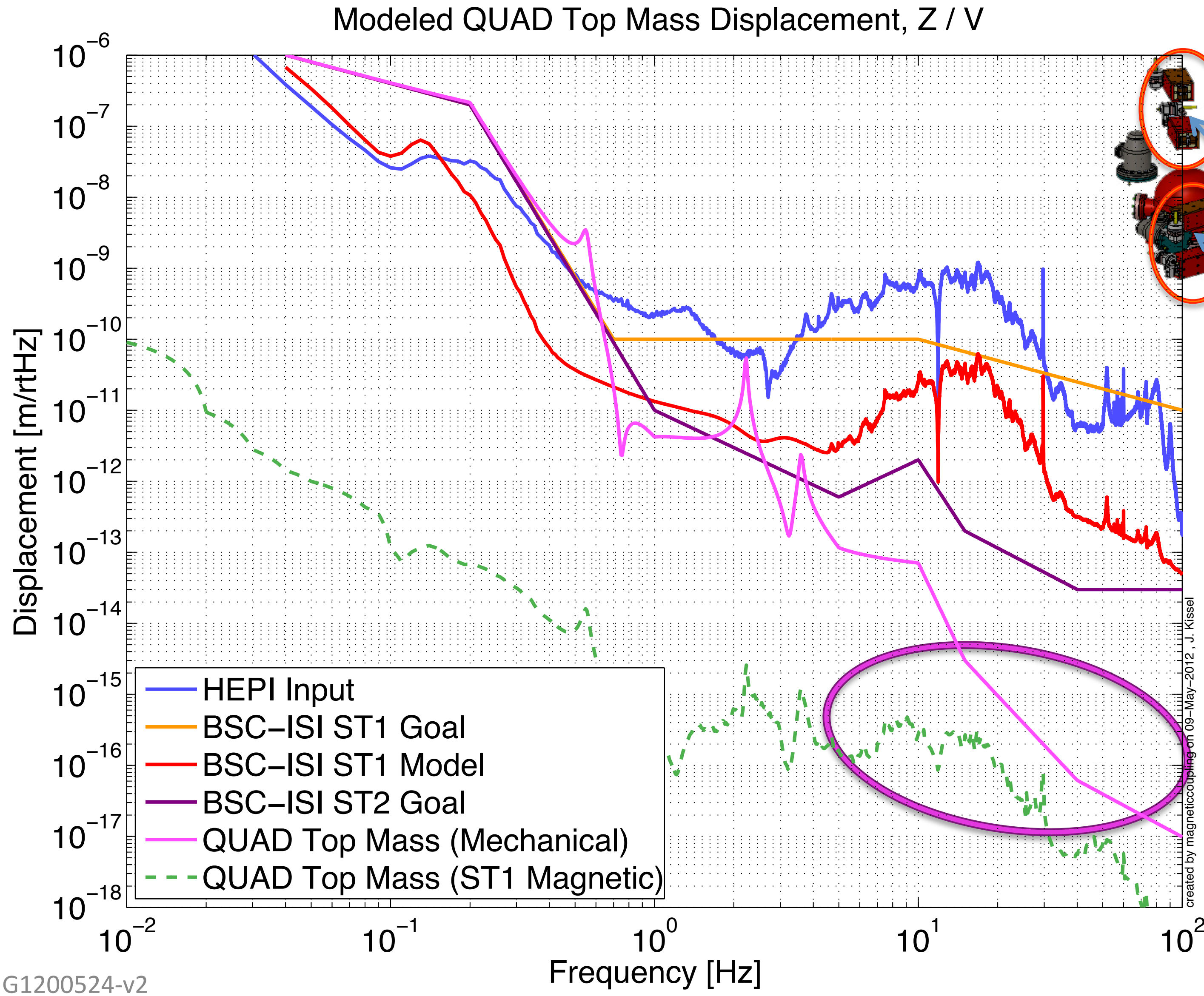
A "Simple" Model
The Answer (Longitudinal)

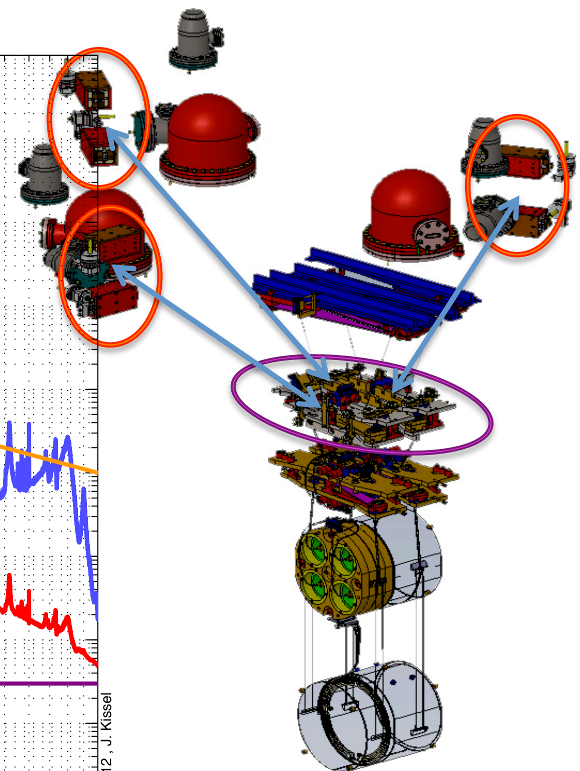




CLOSE.

A "Simple" Model
The Answer (Vertical)





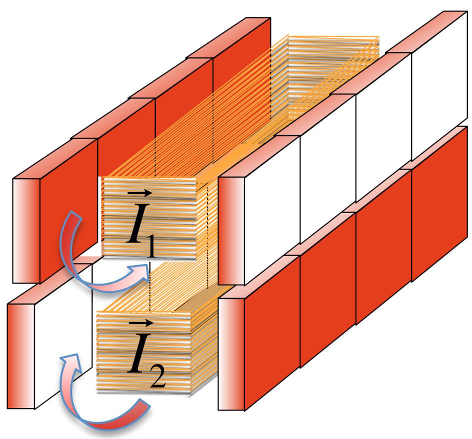
CLOSE.

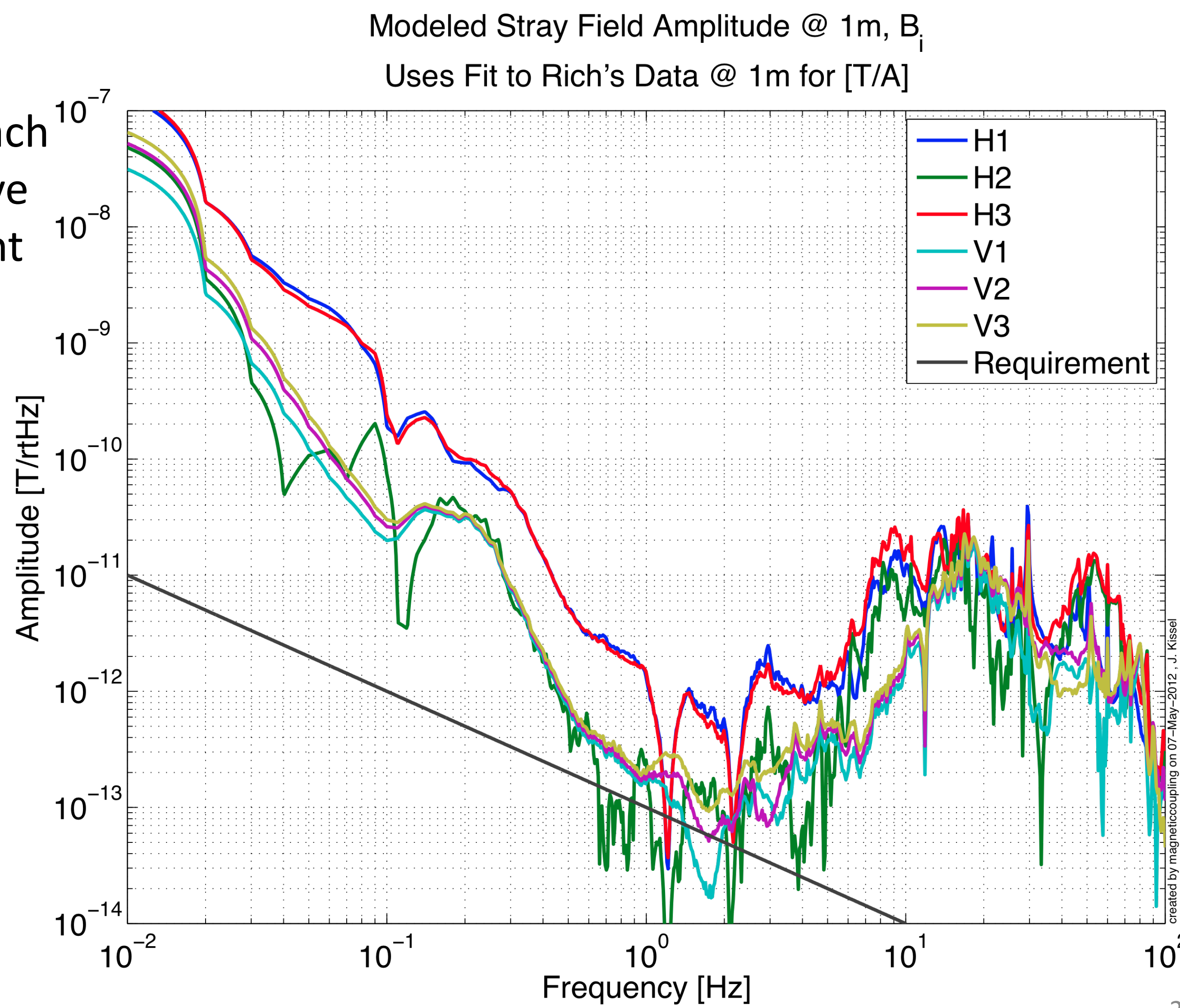
B_{ctrl}

A “Simple” Model
The Culprits (with some grains of salt)

Modeled B_{ctrl} from each ISI actuator is well above the original requirement (interpreted to 1 m distance)

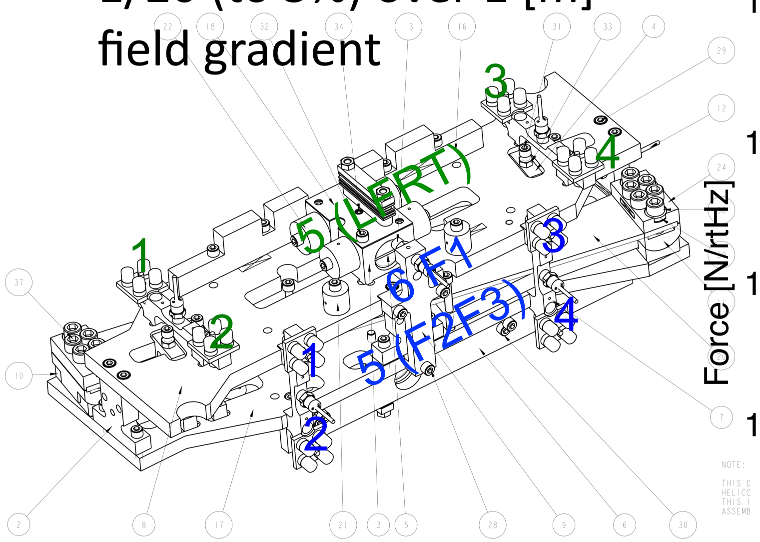
This are summed to form B_{ext}

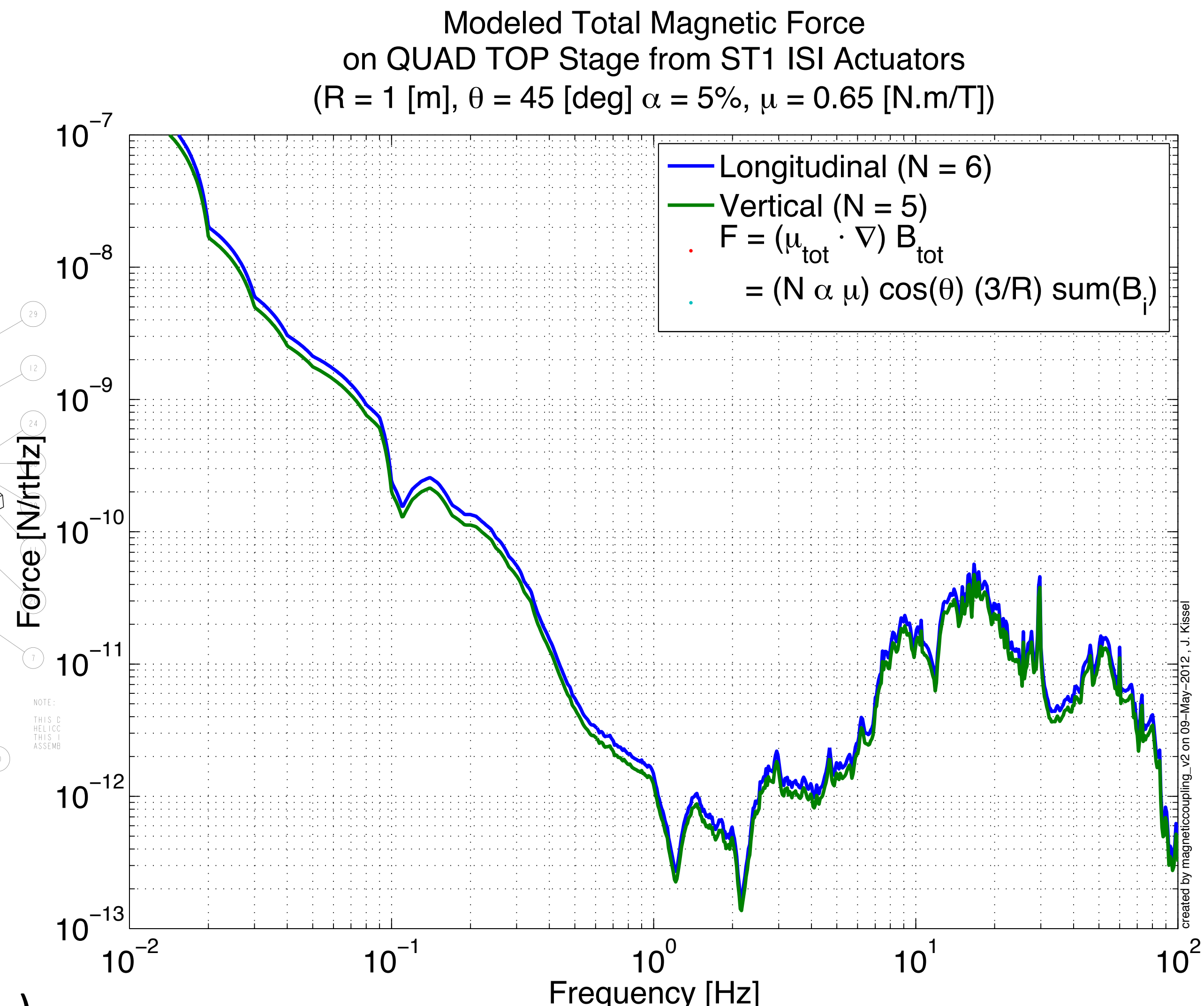




F_{mag} A “Simple” Model
The Culprits (with some grains of salt)

For my dipole moment, I used 6 (L) & 5 (V), 0.65 [J/T] dipoles, reduced by 1/20 (to 5%) over 1 [m] field gradient





Actual residual moment is *definitely* a lot more complicated (but maybe not more than a factor of 10 off…)

Conclusions

- Magnetic coupling between SUS magnets and external fields could be a problem, even with what mitigation is in place
- "Simple" model showed one possible source is close but
  - Still not a great model, and is still over simplified
  - There's a lot that could be improved
  - We need some better / more direct measurements*
  - Infrastructure is in place to add fields, refine model
  - As modeled, ISI Acts don't meet interpreted requirements
- Other sinks (for QUAD): UIM & PUM magnets, Blade Spring ECD Magnets,…
- Other sources (for QUAD): ST2 Actuators, Giant ECD Magnets on ACB, …
- Magnetic short might be worse for HAM Triples since optics are closer to ISI
- Magnetic coupling is **hard** to predict, because we've tried hard already to get rid of the easy stuff
- Should get rid of any loaded guns (e.g. unused ECD magnets on QUAD*)

* Action items

Modeling Magnetic Coupling to Suspensions

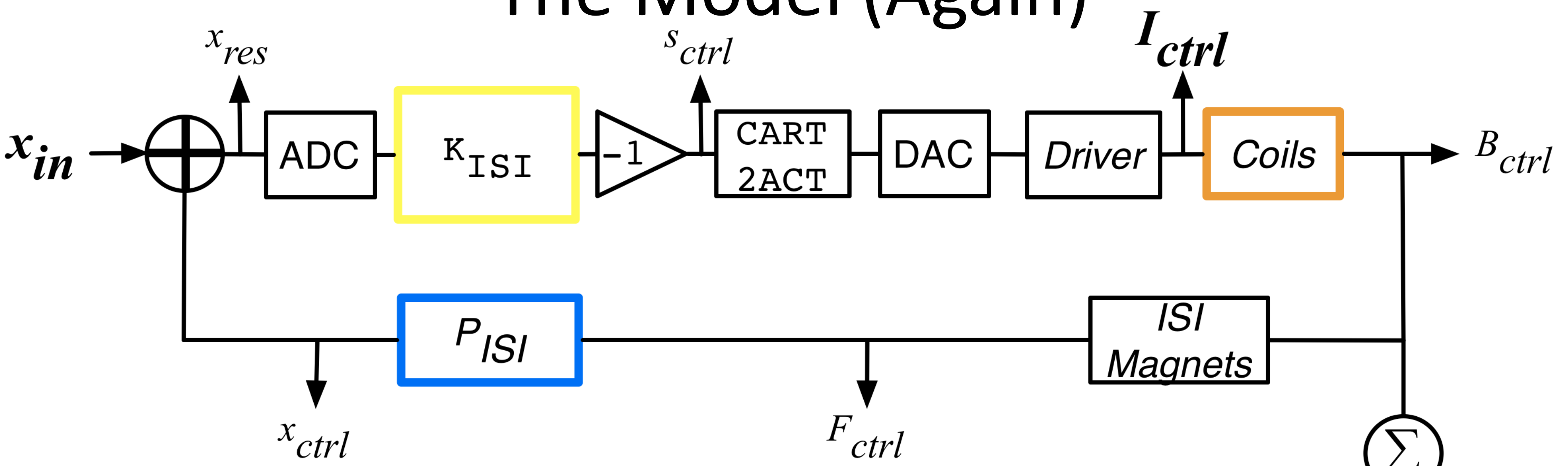
Part 3: The details of the “Simple” Model

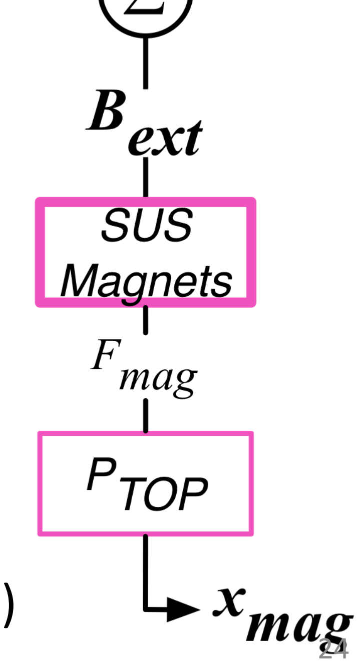
G1200524-v2

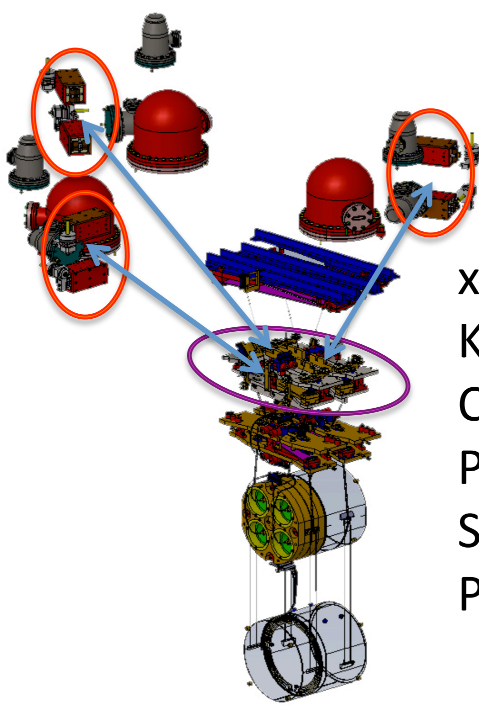
J. Kissel

A “Simple” Model

The Model (Again)



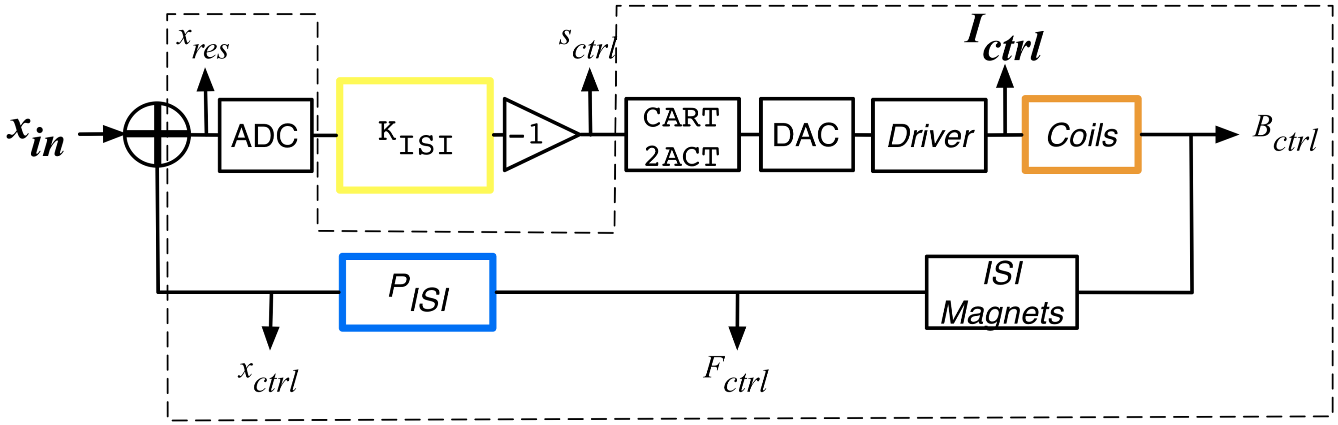




x_{in} [m] – eLIGO HEPI Data, T0900312 (Waldman)
K_{ISI} [ct/m] – Designed for this model (Me)
Coils [T/A] – From old Coarse Actuator (Rich)
P_{ISI} [m/N] – From BSC8 ISI in SeiSVN (Vincent)
SUS Magnets [J/T] – From T1100215 (Rai)
P_{TOP} [m/N]– Production QUAD Model (Barton, Me)

K_{ISI}

A “Simple” Model
ST1 Loop Design: The “Plant”



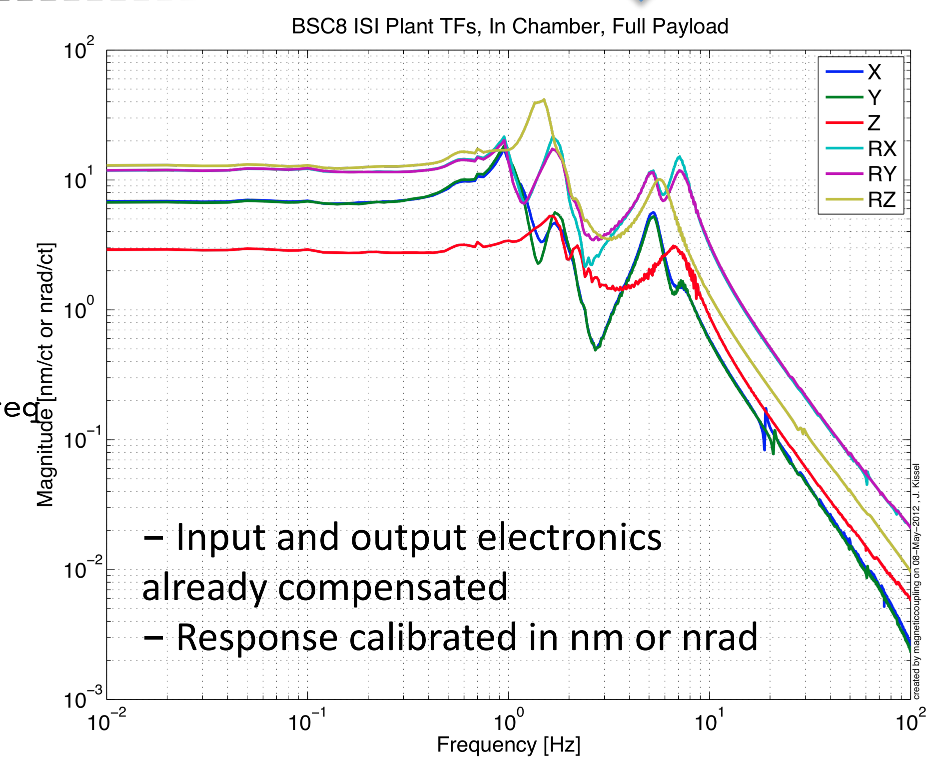
Used real Production BSC-ISI with full payload!

Data stolen and recombined from each of

```
    ${SeiSVN}/seismic/BSC-ISI/H2/ITMY/Data/
Figures/Transfer_Functions/Simulations/
Super_Sensors/
LHO_ISI_BSC8_Super_Sensor_MIMO_ST1_*_Blend_Freq
_0.75Hz.fig
```

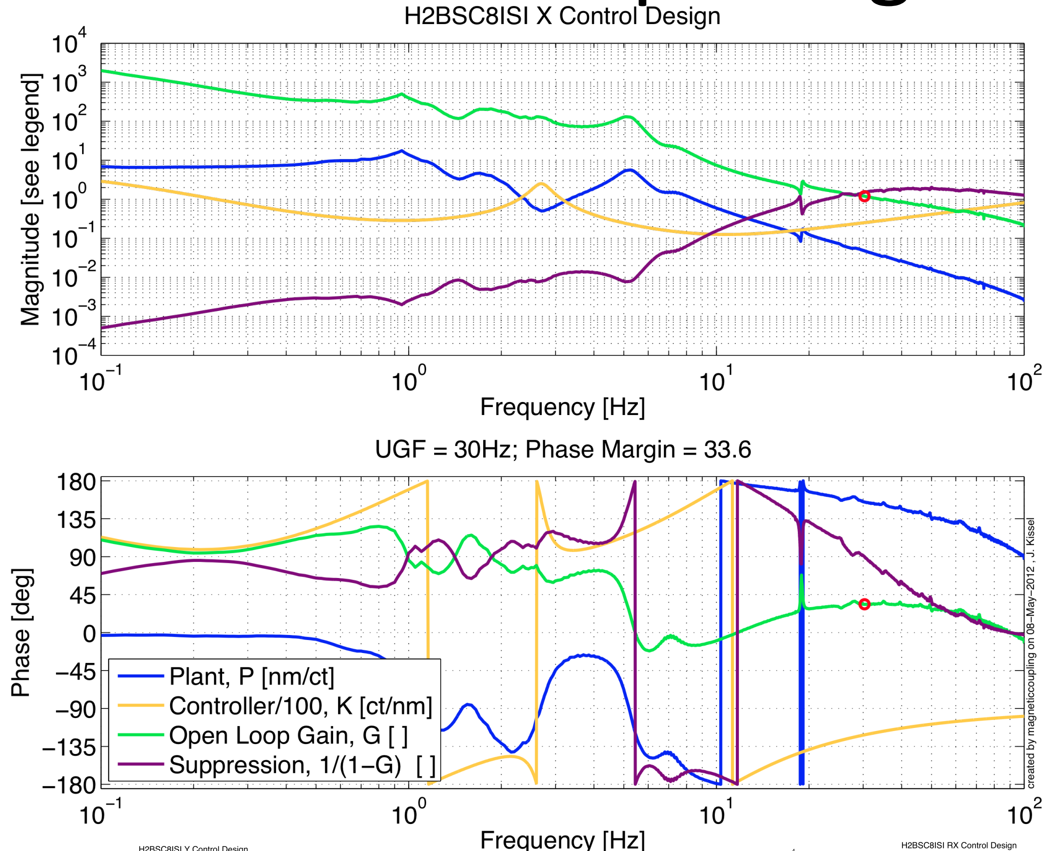
And saved into a new .mat file called

```
${SeiSVN}/seismic/BSC-ISI/Common/Misc/
H2BSC8ISI_SuperSensor_Plant.mat
```



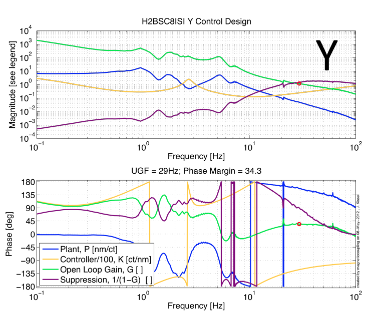
K_{ISI}

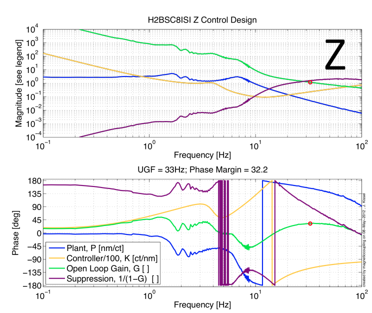
A "Simple" Model
ST1 Loop Design: The Controller

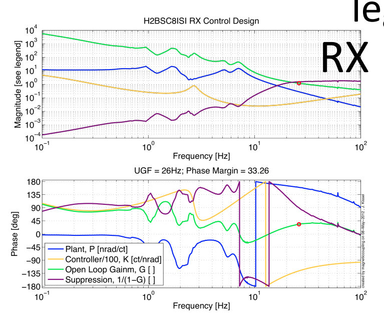


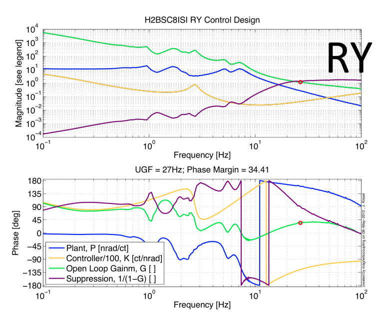
- Remember, controller design is independent of blends
- Went for quick, simple, "vanilla" design -- not perfect
- 30Hz UGFs
- ~35 deg phase margin
- < 2 gain peaking
- At least a factor of 10 suppression at 10 Hz
- Ignored high-frequency

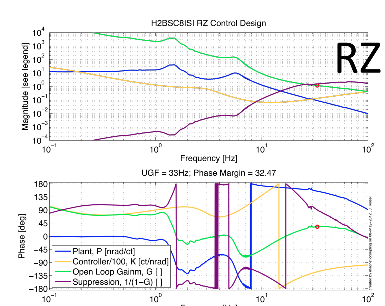
Designed all DOFs, to see **total colocated drive** (sans damping loops)
See attached plot collection for actually legible other DOF plots





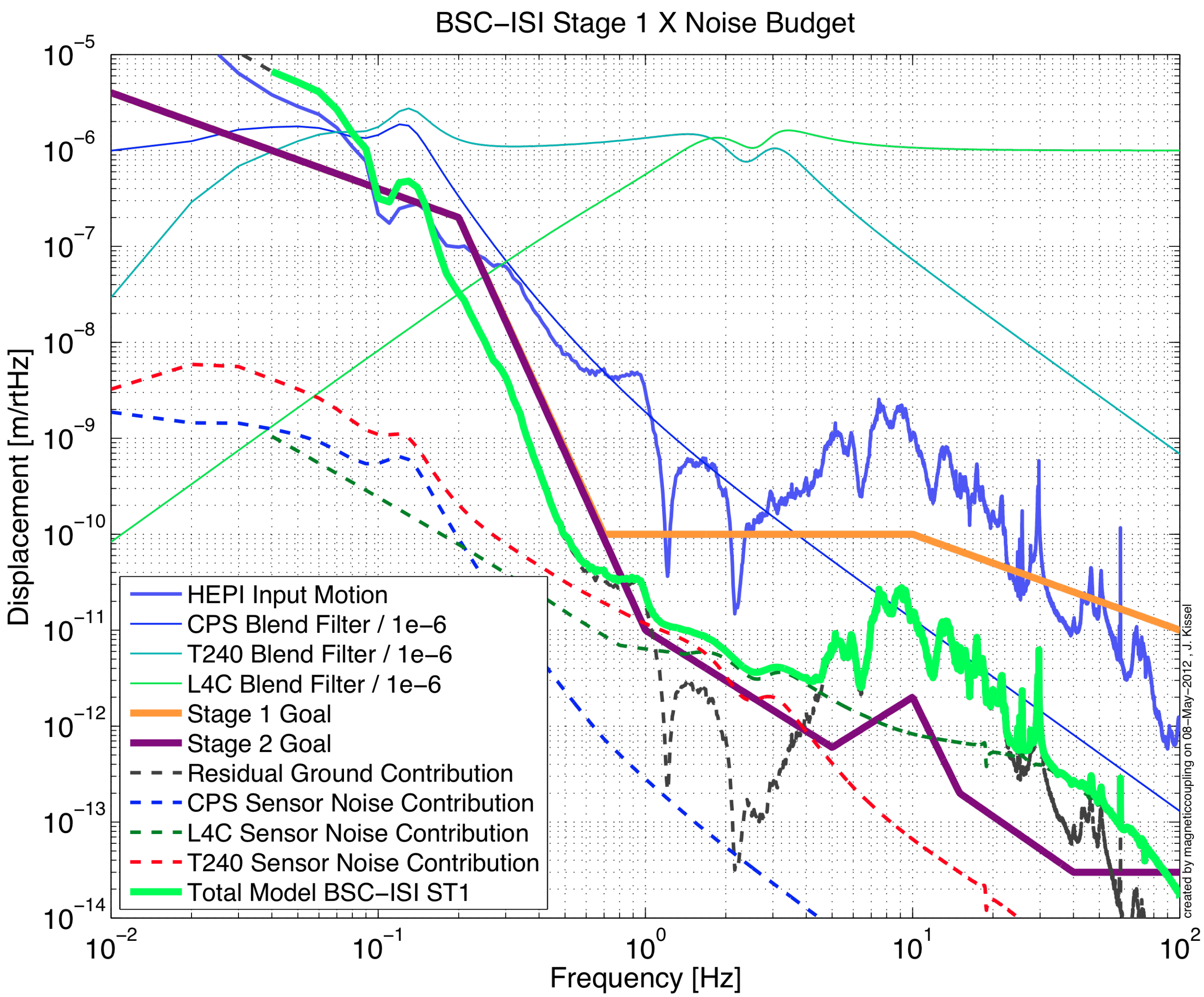






K_ISI

A "Simple" Model
ST1 Loop Design: Proof it's not Crazy

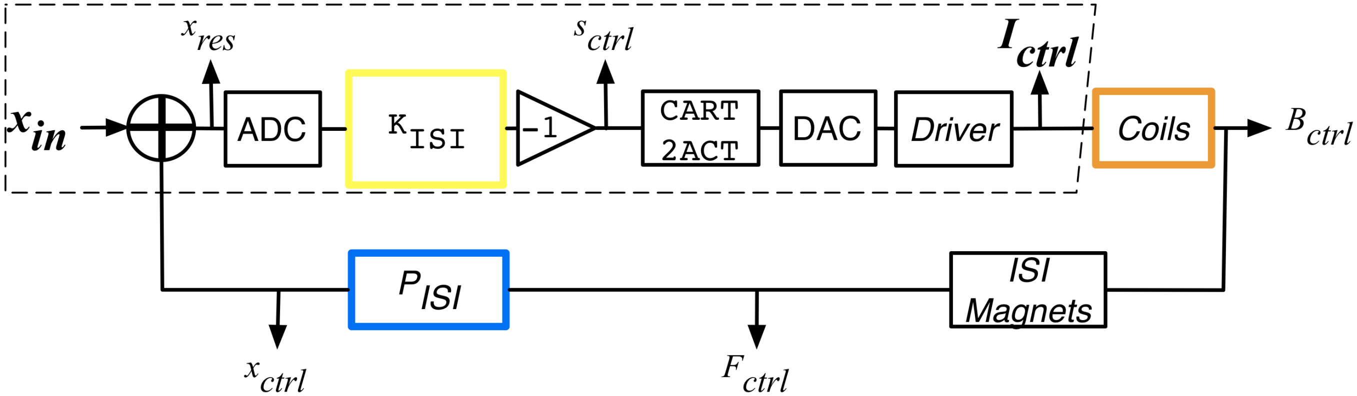


– Sensor noise contribution from SEI_sensor_noise.m (Thanks Brian!)
– HEPI Input Motion from eLIGO HEPI Data, T0900312 (Thanks Sam!)
–Reasonable blend filters (Thanks Rich!)
– No feed forward
– Totally SISO Model (no THC)

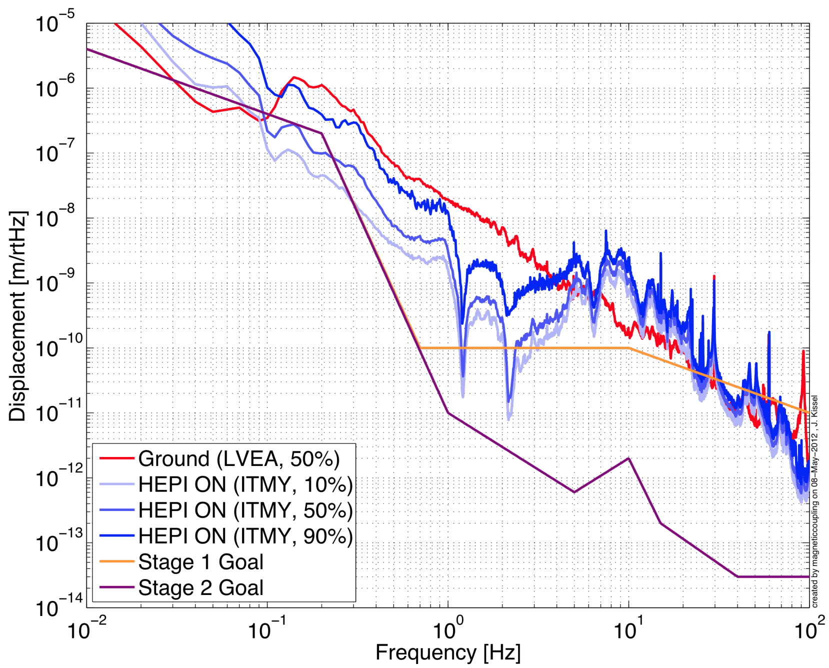
$$x_{ST\,1} = \left(\frac{G}{1-G}\right)\left(\frac{P}{G} - bf_{CPS}\right)x_{in}\cdots$$
$$+\left(\frac{G}{1-G}\right)f_{CPS}n_{CPS}\cdots$$
$$+\left(\frac{G}{1-G}\right)f_{T240}n_{T240}\cdots$$
$$+\left(\frac{G}{1-G}\right)f_{L4C}n_{L4C}$$

I_{ctrl}

A "Simple" Model
The total current output



– Used 50th Percential eLIGO HEPI Motion for
–Used real transformation CART2ACT matrix:
– aLIGO_BSC_ISI_Matrices_Y_Direction.mat
– Assumed all analog electonics have been perfectly compensated

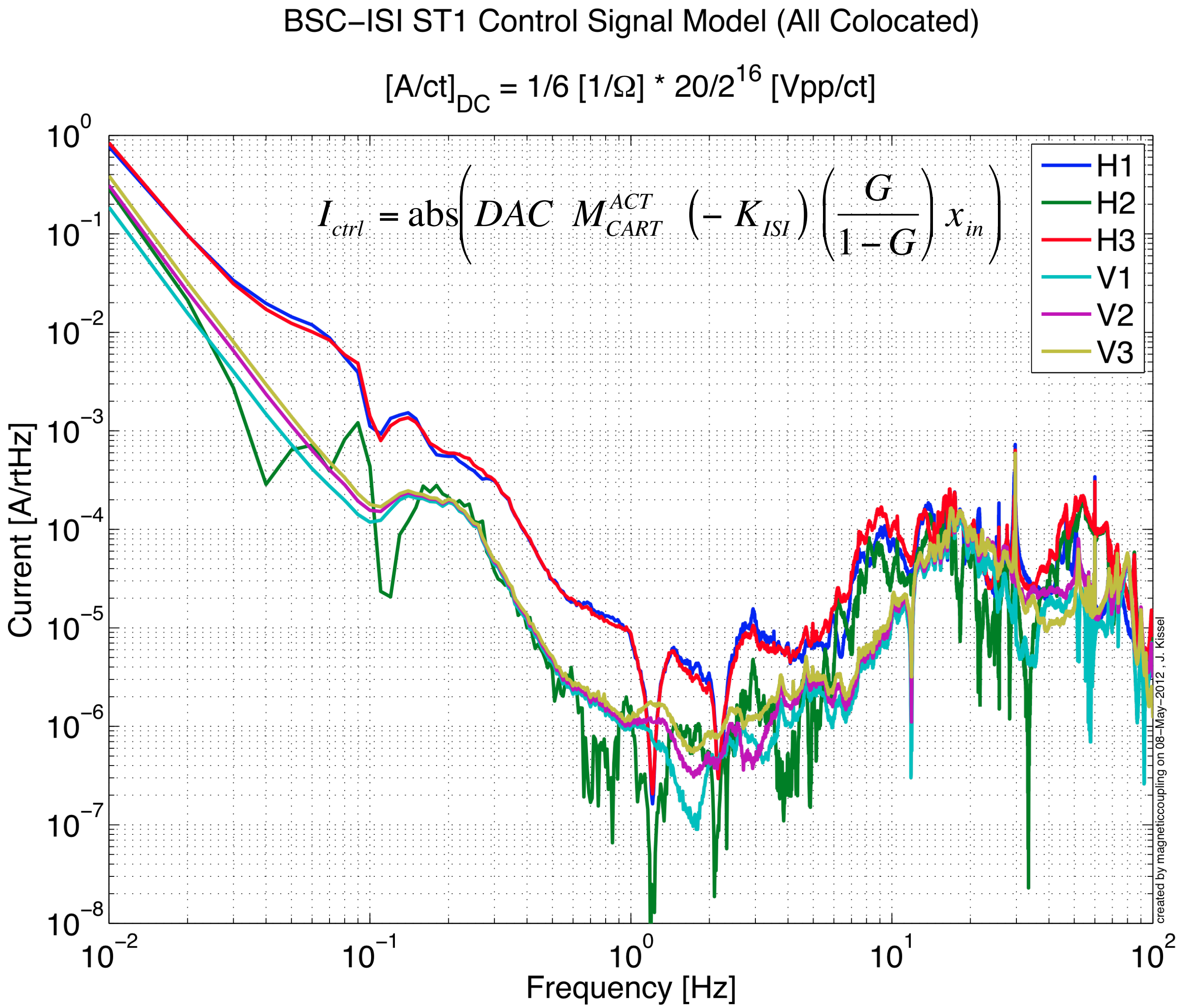



```
ctpV = 2^16/20;           % [ct/V] For a General Standards
                          % 16-bit DAC
VpA  = 6;                 % [V/A]  or [Ohms] Coil
                          % resistance of Large Actuator,
                          % see e.g. T0900564
Apct = 1/(ctpV * VpA);    % [A/ct] drive calibration
                          % (assume frequency
                          %  dependence has been properly,
                          %  of analog electronics has
                          %  perfectly compensated)
```

$$I_{ctrl} = \mathrm{abs}\left(DAC \;\; M_{CART}^{ACT} \;\; \left(-K_{ISI}\right) \left(\frac{G}{1-G}\right) x_{in} \right)$$

I_{ctrl}

A "Simple" Model
The total current output



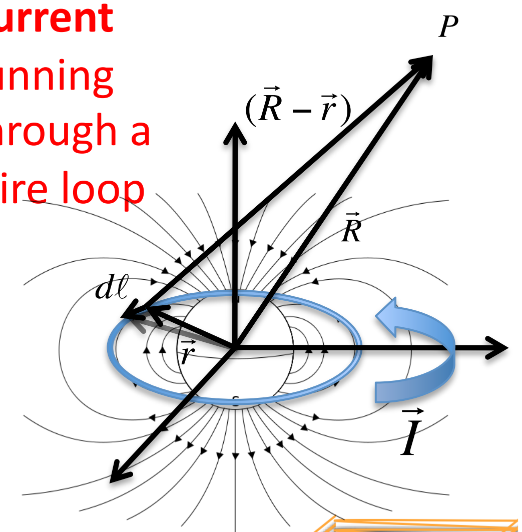
A "Simple" Model
The Coil Actuators [T/A]: "Simple" Dipole

Remember from slide 5, we calculated the field of a loop of wire, with an oscillating current:

$$B_r = \frac{2\mu_0 A\cos\theta}{4\pi} I_0 \left[\frac{1}{R^3}\cos[\omega(t-R/c)] - \frac{\omega}{R^2 c}\sin[\omega(t-R/c)]\right]$$

$$B_\theta = \frac{\mu_0 A\sin\theta}{4\pi} I_0 \left[\left(\frac{1}{R^3} - \frac{\omega^2}{rc^2}\right)\cos[\omega(t-R/c)] - \frac{\omega}{R^2 c}\sin[\omega(t-R/c)]\right]$$

$$E_\phi = \frac{\mu_0 A\sin\theta}{4\pi} I_0 \left[\frac{\omega^2}{Rc}\cos[\omega(t-R/c)] + \frac{\omega^2}{R}\sin[\omega(t-R/c)]\right]$$



But thankfully, we're in a non-relativistic regime, where

$$\frac{\omega R}{c} << \omega t \qquad \frac{\omega}{R^2 c} << \frac{1}{R^3} \qquad \frac{\omega^2}{Rc^2} << \frac{1}{R^3} \qquad \frac{\omega}{R^2} << \frac{\omega^2}{Rc}$$

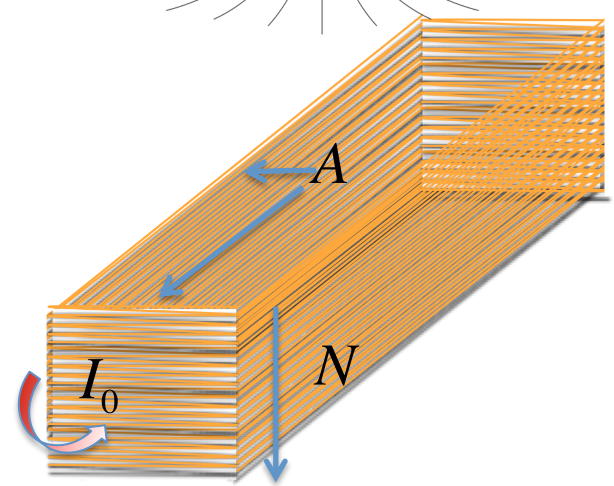
So our equations reduce to

$$B_r = \frac{2\mu_0 A\cos\theta}{4\pi} I_0 \left[\frac{1}{R^3}\right]$$

$$B_\theta = \frac{\mu_0 A\sin\theta}{4\pi} I_0 \left[\frac{1}{R^3}\right]$$

$$E_\phi = \frac{\mu_0 A\sin\theta}{4\pi} I_0 \left[\frac{\omega^2}{R}\right]$$

(where I've dropped terms involving $\sin(\omega t)$ and $\cos(\omega t)$ because we're already in the frequency domain)

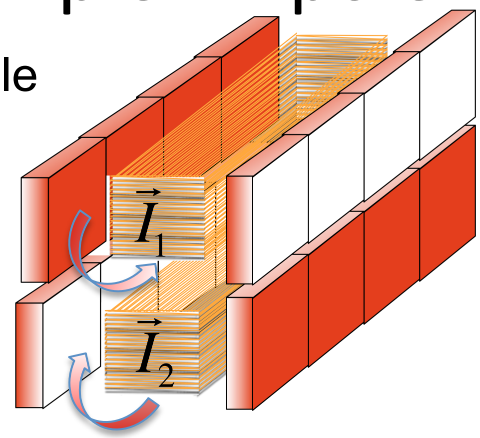


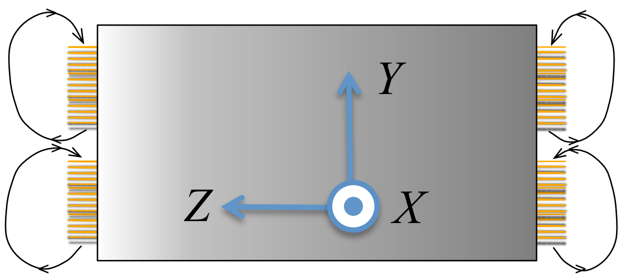
Then multiply by N turns to get a solenoid dipole model

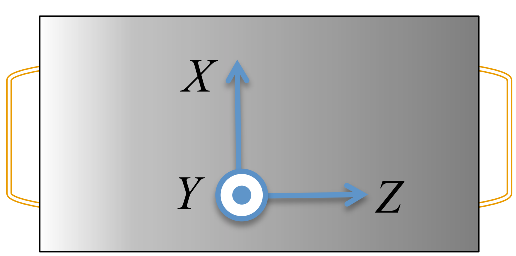
A “Simple” Model

The Coil Actuators: They’re **not** a “Simple” Dipole

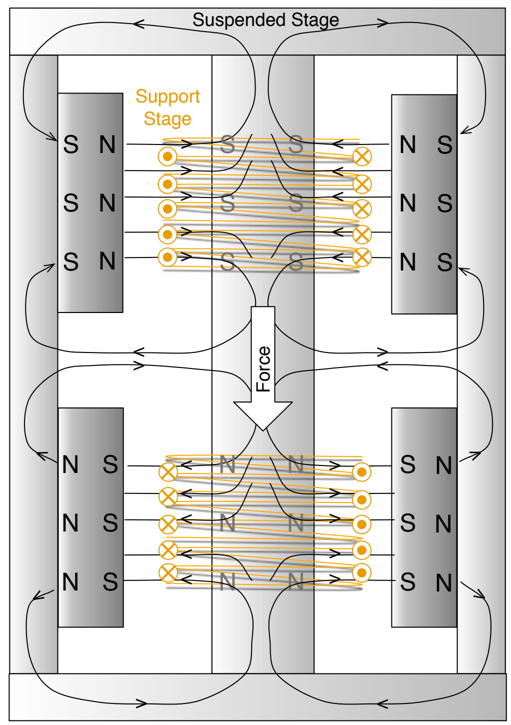
Again, there are two counter-wound coils to create a quadrapole
Also, they’re shielded in the “X” and “Y” direction

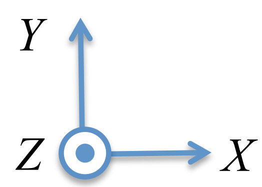






Magnetic flux is confined to the ferromagnetic material





Sect. 5.13 Effect of a Circular Hole in a Perfectly Conducting Plane 203

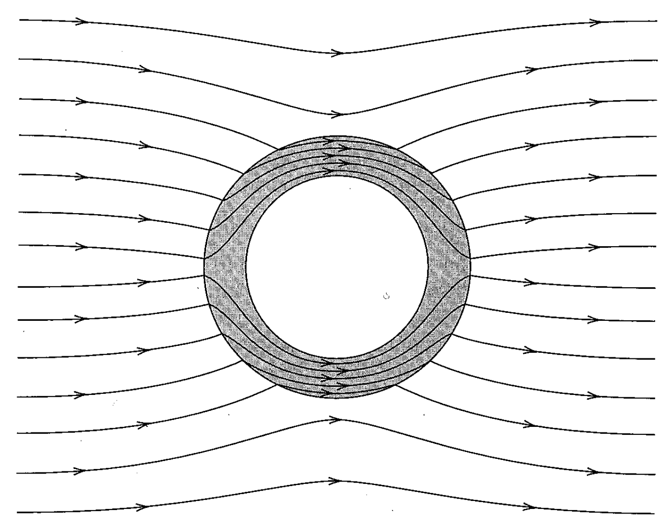


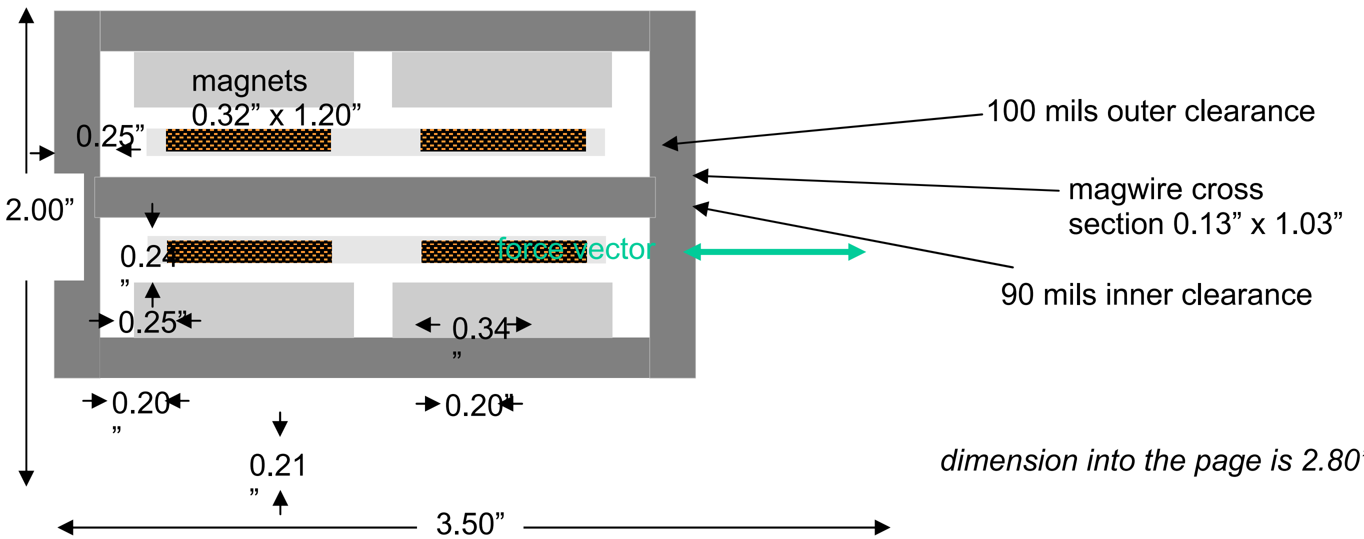
Figure 5.14 Shielding effect of a shell of highly permeable material.

Jackson has a section on magnetic shielding if you’re interested…

Coils

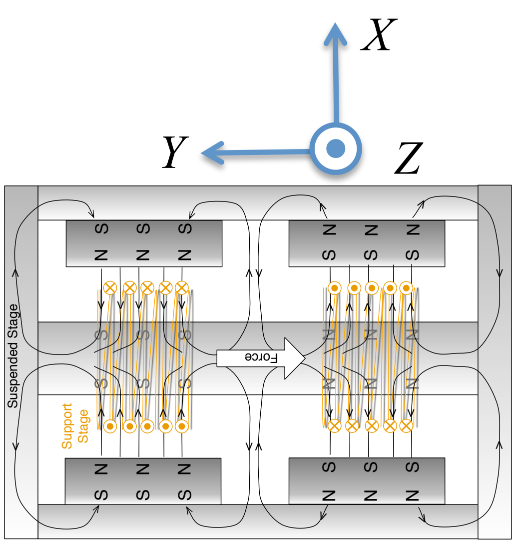
A “Simple” Model

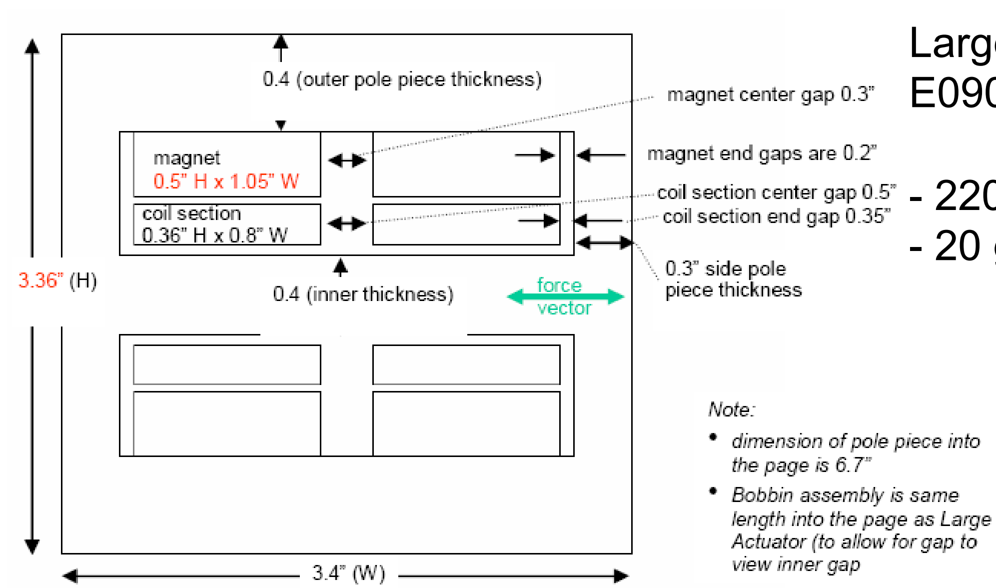
The Coil Actuators: Dimensions



Small Actuators
DCC # Pending

- 258 turns / coil (6x43),
- 24 gauge wire





Large Actuators
E0900037

- 220 turns/coil (10x22)
- 20 gauge wire

Coils

A “Simple” Model

The Coil Actuators: Measured Data vs. Radius

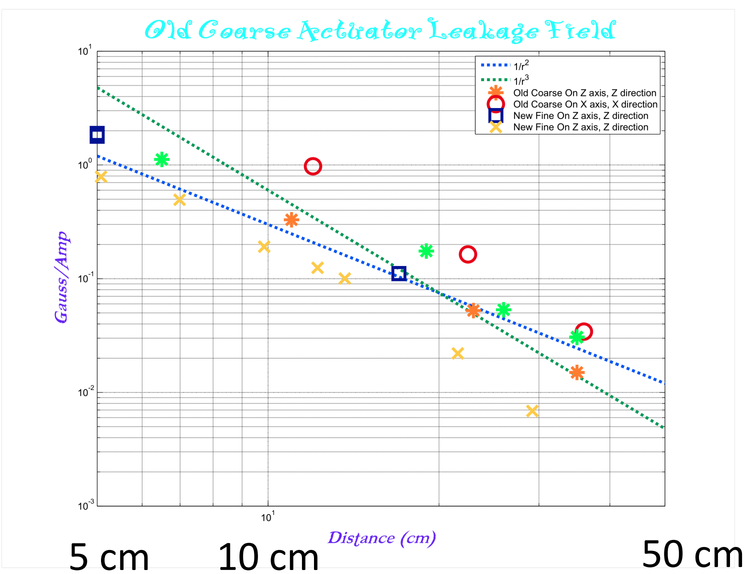
Back when we were worried about magnetic coupling to ISI sensors, Rich made some useful measurements of the stray fields from real actuators

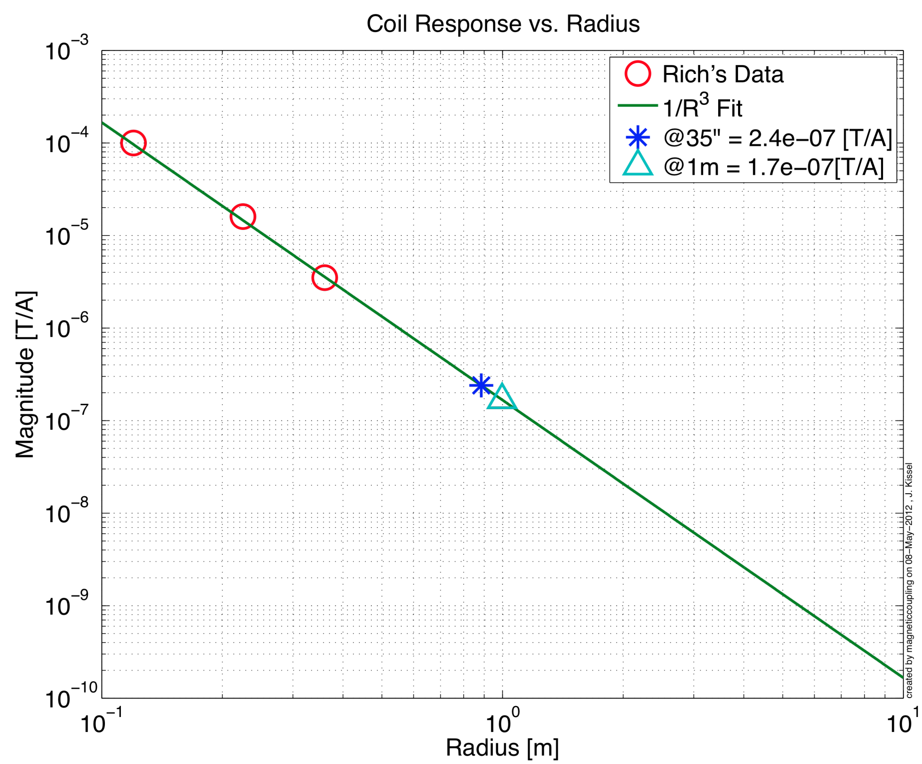
But, he was looking for near field, stray magnetic fields and it was before the re-design of the large actuators (to increase the gap between magnets and coils – it shouldn’t make that much of a difference)

It’s a Start!!

I took “worst” case: Old Coarse Acts “X on X,” and extrapolated as $1/R^3$ to 1m

His Data @ DC vs. Radius (as measured by a magnetometer)





Coils

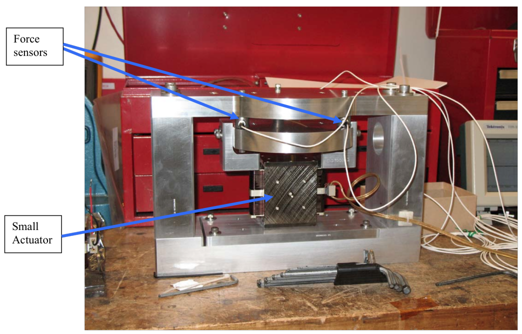
A "Simple" Model

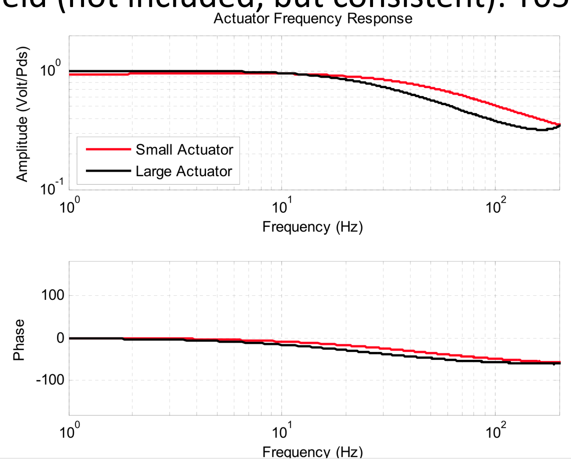
The Coil Actuators [T/A]: Measured Data vs. Freq

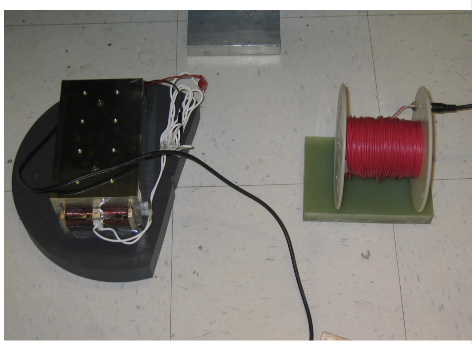
Concerned about frequency dependence of the [T/A] generator constant, both Rich and Fabrice made independent measurements of the frequency response of coil drivers (See [old] SEIl Log 1725 and T0900226 respectively)

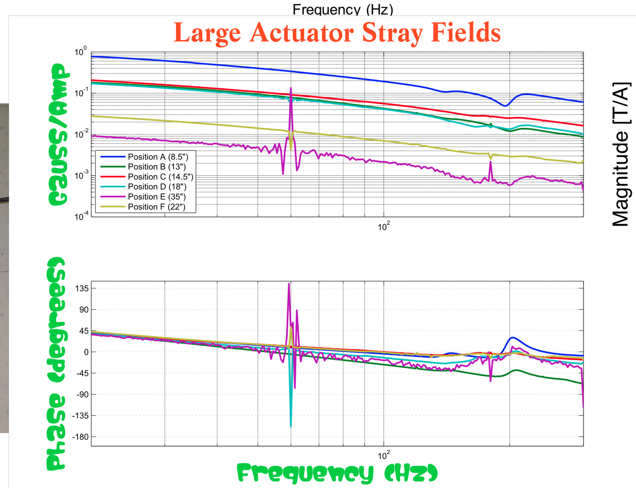
Fabrice measured the force on the magnets, Rich measured the leakage field, both show a roll-off around 30 Hz.

For other work by Robert Schofield (not included, but consistent): T050087 and LHO i/eLOG May 11, 2008

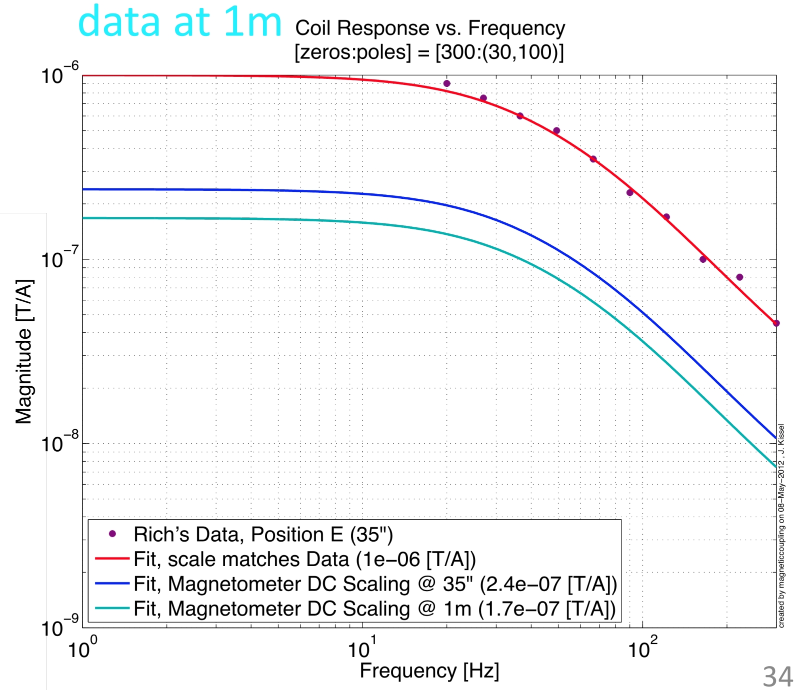








I took Rich's furthest measurement @ 35," fit it to a 30Hz roll off, and scaled it to his magnetometer DC data at 1m



B_{ctrl} A “Simple” Model

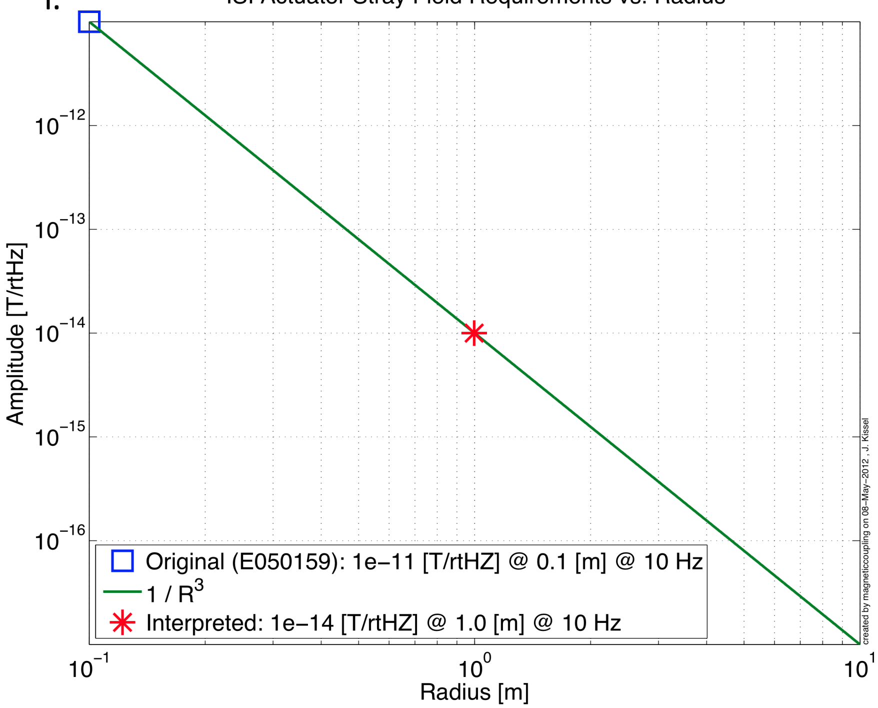
Stray Fields [T]: Interpreting the Reqs.

Requirements:

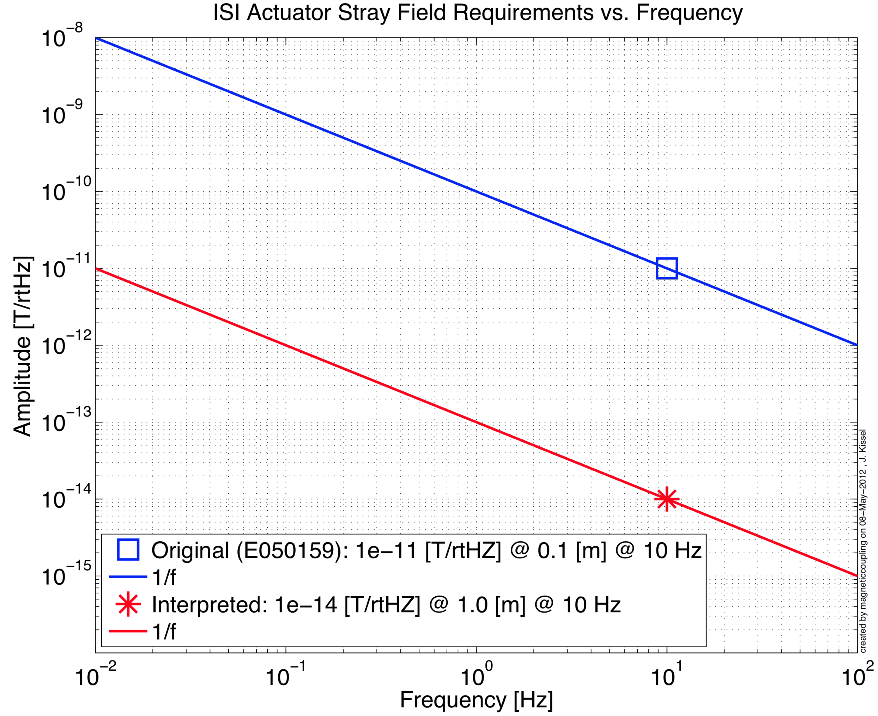
−From **T010007**, 4.2.7 (Barton, Robertson, Fritschel, Shoemaker, Willems)
“… We require that [technical noise] be … 10% [the] amplitude of … pendulum thermal noise. Sources include … ambient magnetic field fluctuations at the magnetic actuators… .”

−From **E050159**, Sect. 1.1.4.5 (D. Coyne)
“… max magnetic field and gradient, at … 10 cm below the optics table, due to SEI Actuators … shall be < 10pT/rtHz and 20 [pT.m^{-1}/rtHz] at 10 Hz, varying as 1/f.”

ISI Actuator Stray Field Requirements vs. Radius



ISI Actuator Stray Field Requirements vs. Frequency



B_{ctrl}

A "Simple" Model

Stray Fields [T]: "Simple" Dipole vs. Meas.