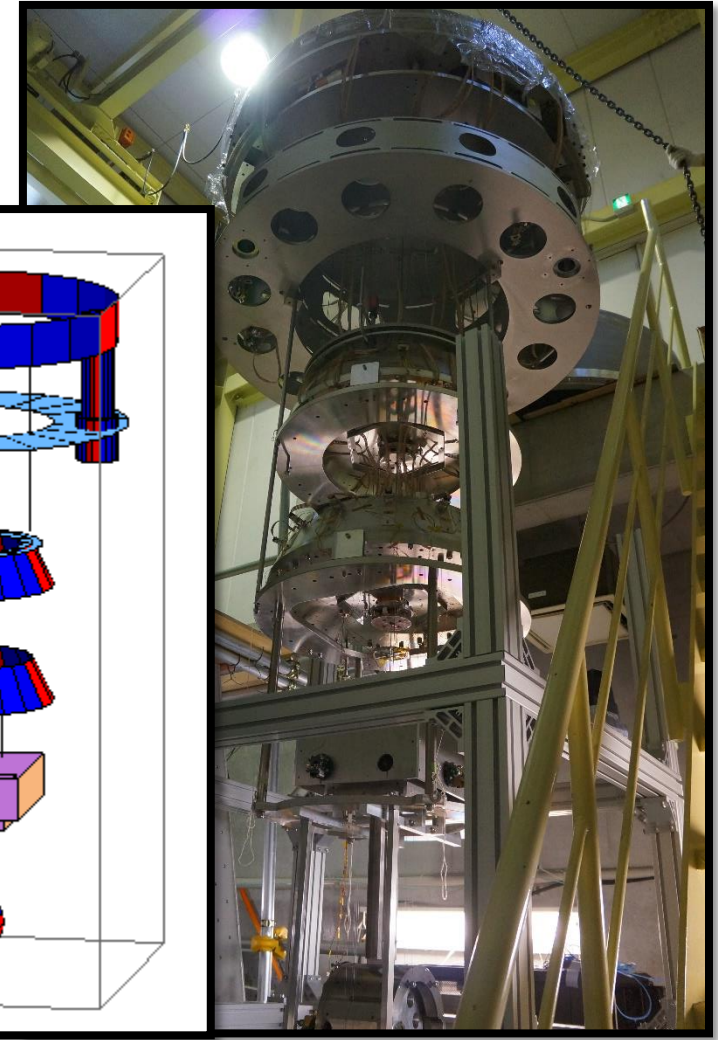
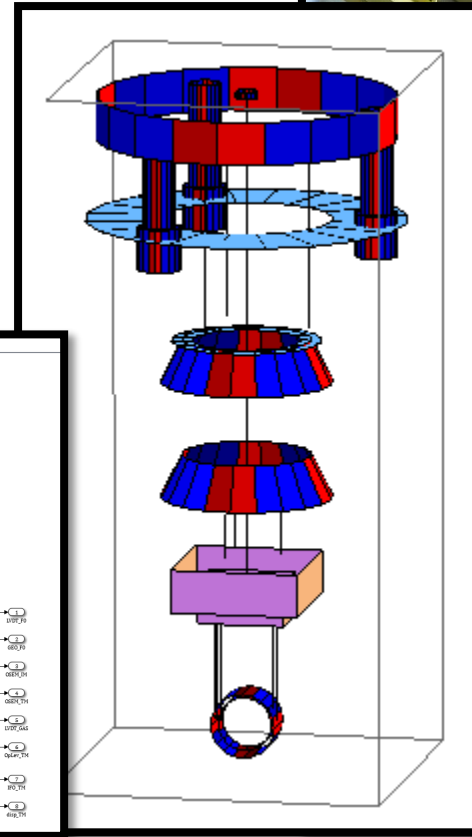
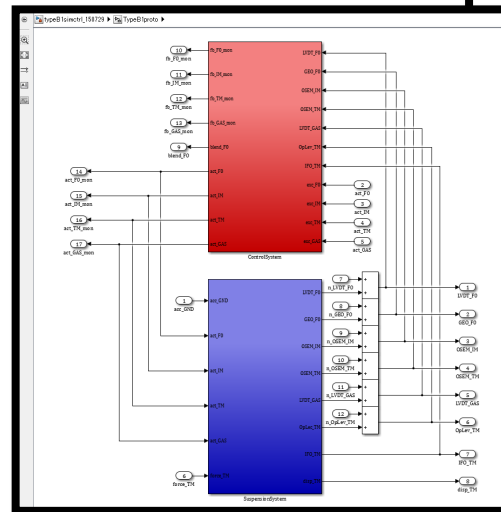


# Modeling tools in KAGRA for seismic and payload mechanical systems

Yoshinori Fujii  
U. of Tokyo / NAOJ

with the cooperation of  
KAGRA VIS team



# Contents

## ❖ Intro

### ☐ KAGRA / Suspension Configuration /

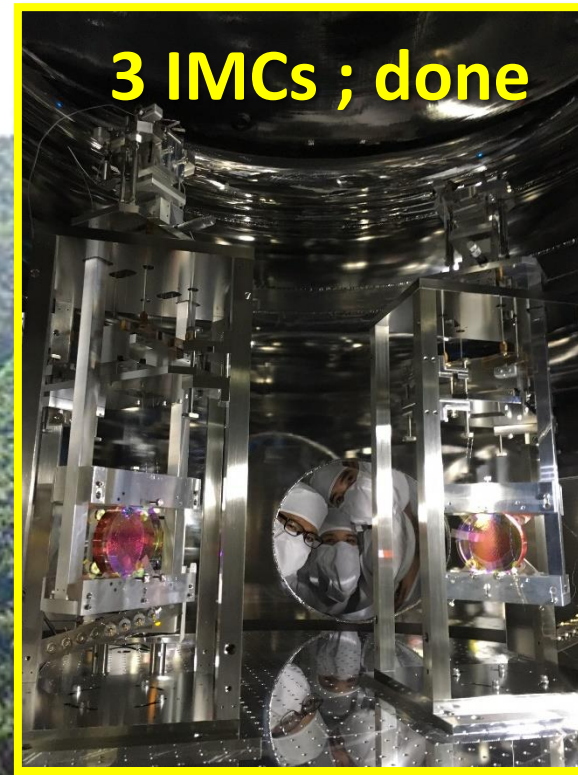
### ☐ Suspension modeling

#### ☐ Modeling tools

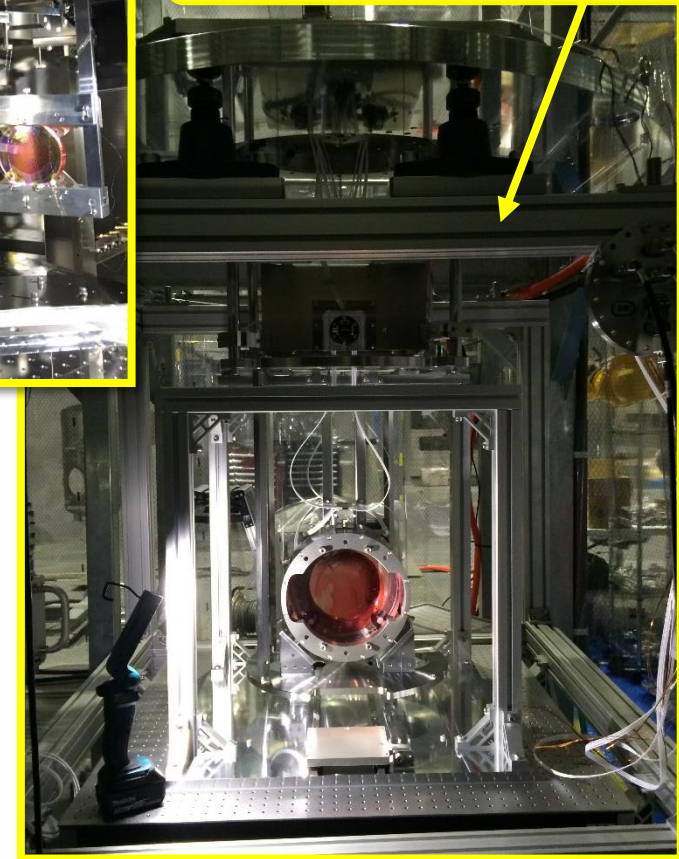
#### ☐ Implementation to BS SAS prototype exp.

# Intro : KAGRA

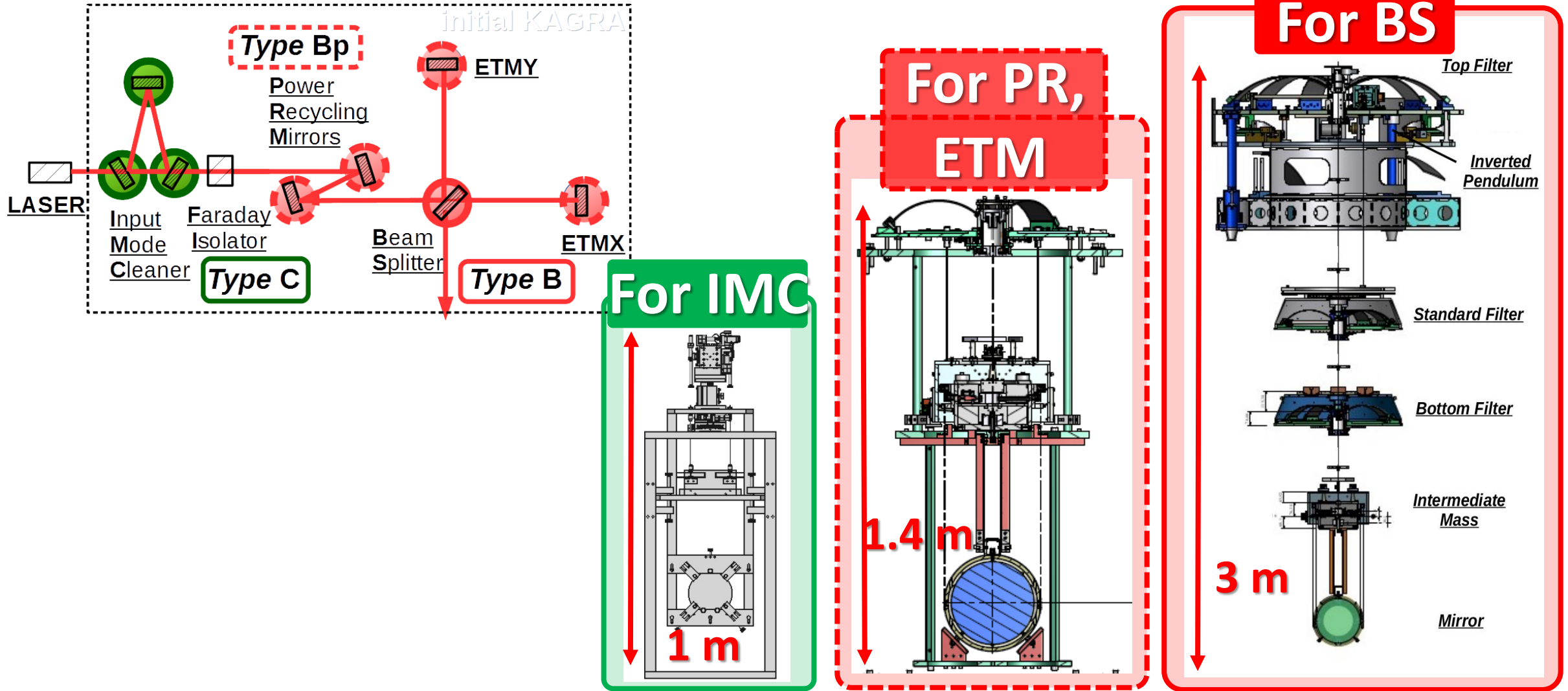
We are NOW installing  
iKAGRA SASs in the tunnel.



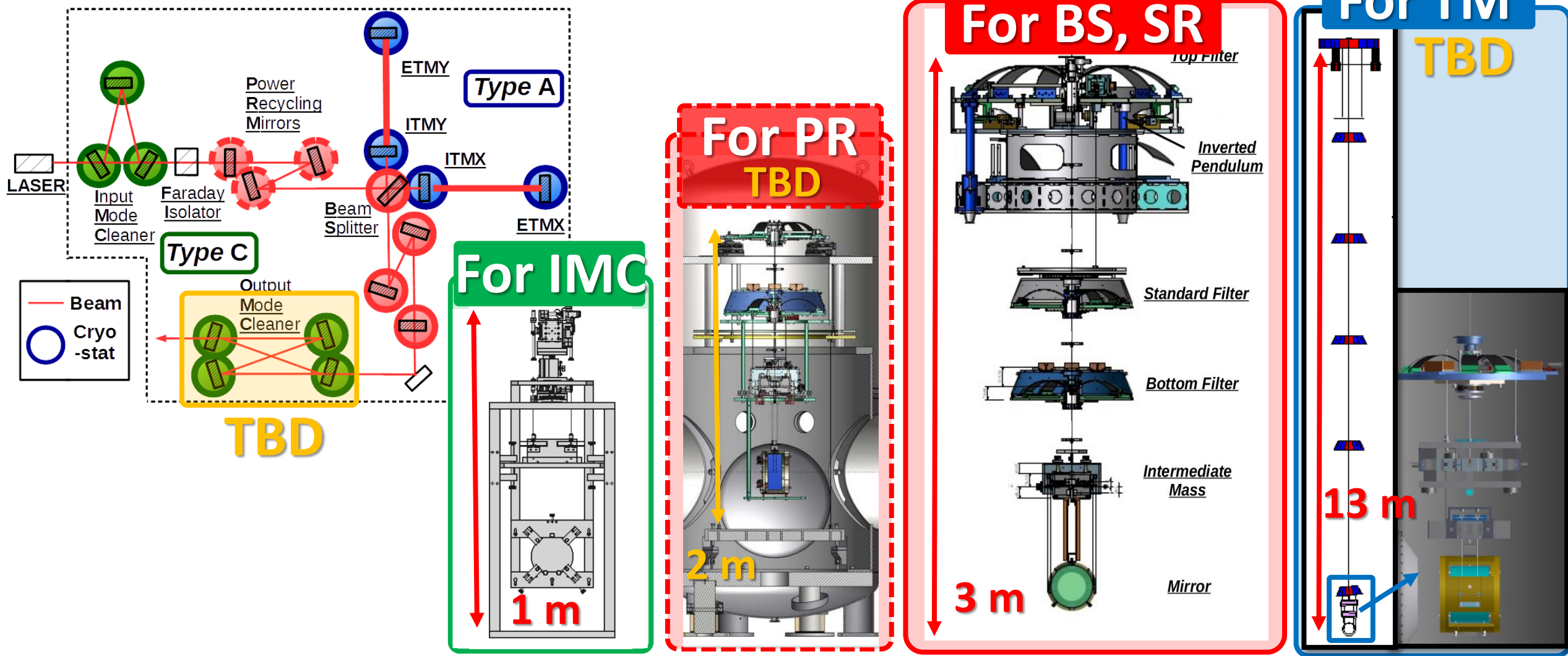
2 PRs & 2 ETMs ;  
Confirming  
installation  
procedure



# ❖ iKAGRA Suspension Configuration ( for a test run )



# ❖ bKAGRA Suspension Configuration ( for observation )



# Contents

## □ Intro

### □ KAGRA / Suspension Configuration /

## ❖ Suspension modeling

### □ Modeling tools

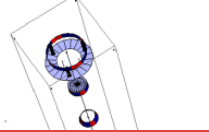
### □ Implementation to BS SAS prototype exp.

❖ Modeling tools : We have 2 ways.

# Passive Model

## Mechanical Model

**SUMCON** in *Mathematica*  
suspension odel    structor



Main Concern :

- Seismic noise
- Vibration from heat links
- Eddy current damping
- Suspension thermal noise

State-Space  
Model



COMSOL  
MULTIPHYSICS



Main Concern :

- Heat link  
Transfer func.

# Passive Model Active Model

## Control Model

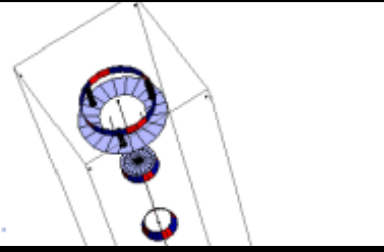


Main Concern :

- Controllability
- Servo filter design
- Sensor / Actuator noise

## ❖ Modeling tools : **Mechanical model**

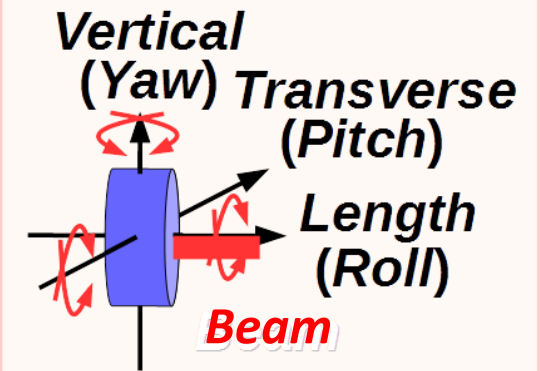
**SUMCON** *in Mathematica*  
suspension model structure



is **3D rigid body simulation software** created by T Sekiguchi.

### Assuming

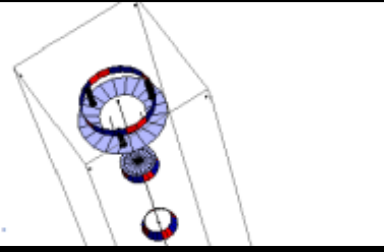
- ❑ 6 DoFs( 3 translation, 3 rotation ) for each mass
- ❑ No deformation of masses
- ❑ Non-mass wire / No wire string vibration
- ❑ GAS → vertical spring moving for only one direction





## ❖ Modeling tools : **Mechanical model**

**SUMCON** *in Mathematica*  
suspension odel    structor



is **3D rigid body simulation software** created by T Sekiguchi.

Assuming

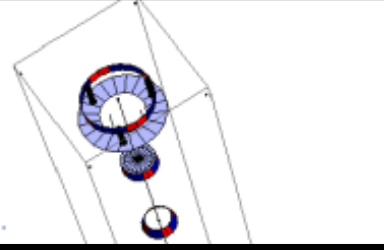
More detailed information is here :

T sekiguchi, *LCGT internal Document* : **JGW-P1200770** (2012)

<http://gwdoc.icrr.u-tokyo.ac.jp/DocDB/0007/P1200770/002/MasterThesis.pdf>

# ❖ Modeling tools : **Mechanical model**

**SUMCON** *in Mathematica*  
suspension model structure



## Required information

Mass & Mol

Wire

Vertical spring

IP Heat link

Eddy current damper

Construct  
linearized  
Eq of M

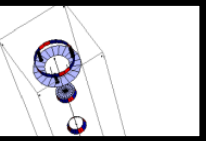
## Main outcomes

Transfer function :  
Displacement & Force / Torque

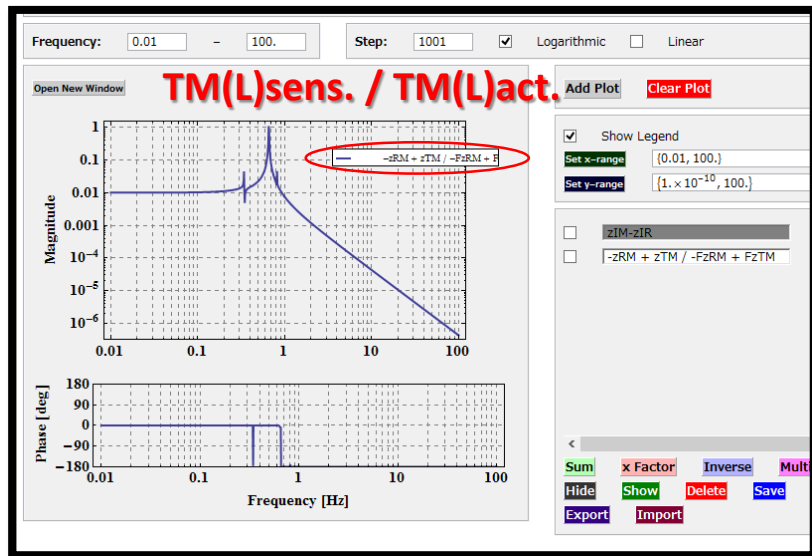
Eigen mode List & 3D shape

Thermal & Seismic noise plot

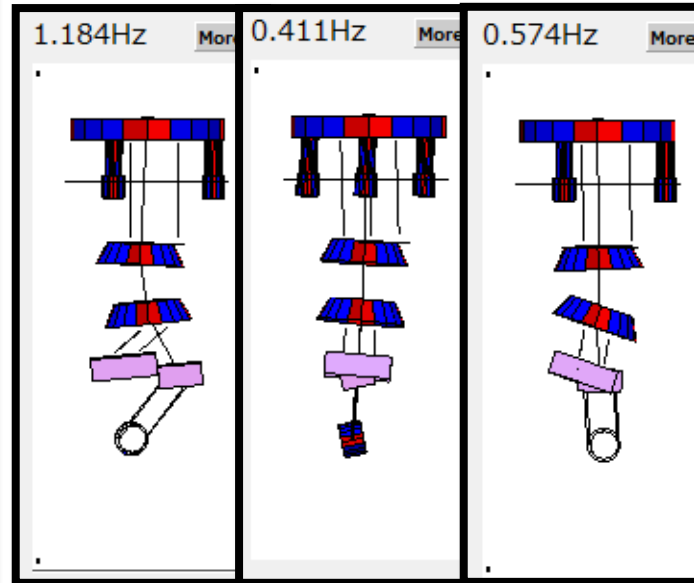
# Modeling tools : Mechanical model



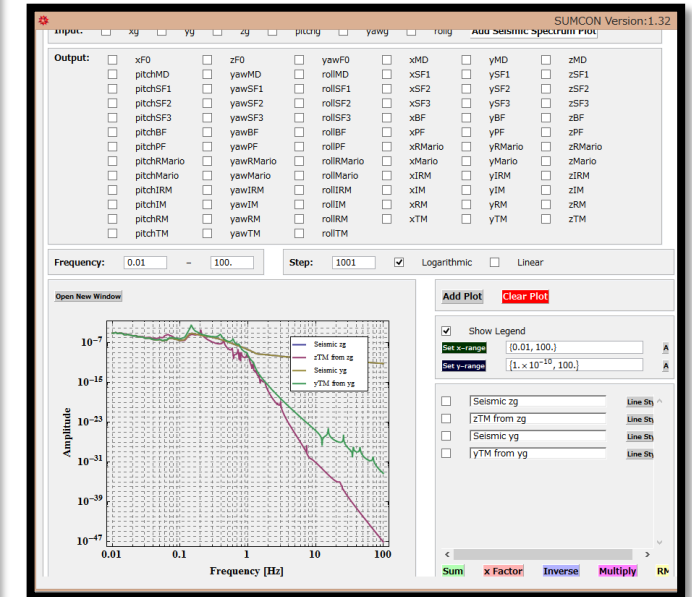
## Displacement & Force / Torque Transfer function



## Eigen frequency / Eigen mode shape



## Thermal & Seismic noise plot

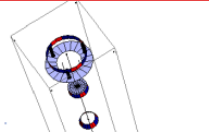


❖ Modeling tools : We have 2 ways.

# Passive Model

## Mechanical Model

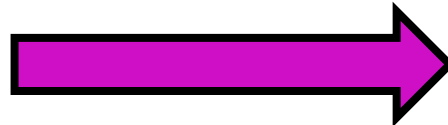
**SUMCON** in *Mathematica*  
suspension odel    structor



Main Concern :

- Seismic noise
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- Eddy current damping
- Suspension thermal noise

State-Space  
Model



COMSOL  
MULTIPHYSICS

Main Concern :

- Heat link  
Transfer func.

# Passive Model Active Model

## Control Model



Main Concern :

- Controllability
- Servo filter design
- Sensor / Actuator noise

## ❖ Modeling tools : **Active model**



is used in active controlling simulation

### Required information

Mass & Mol

Wire

Vertical spring

IP Heat link

Eddy current damper

Servo filter

Construct  
State-space  
model

### Main outcomes

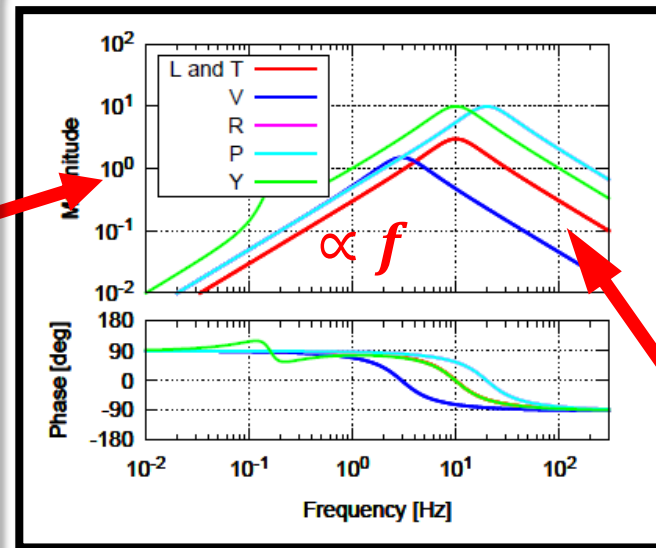
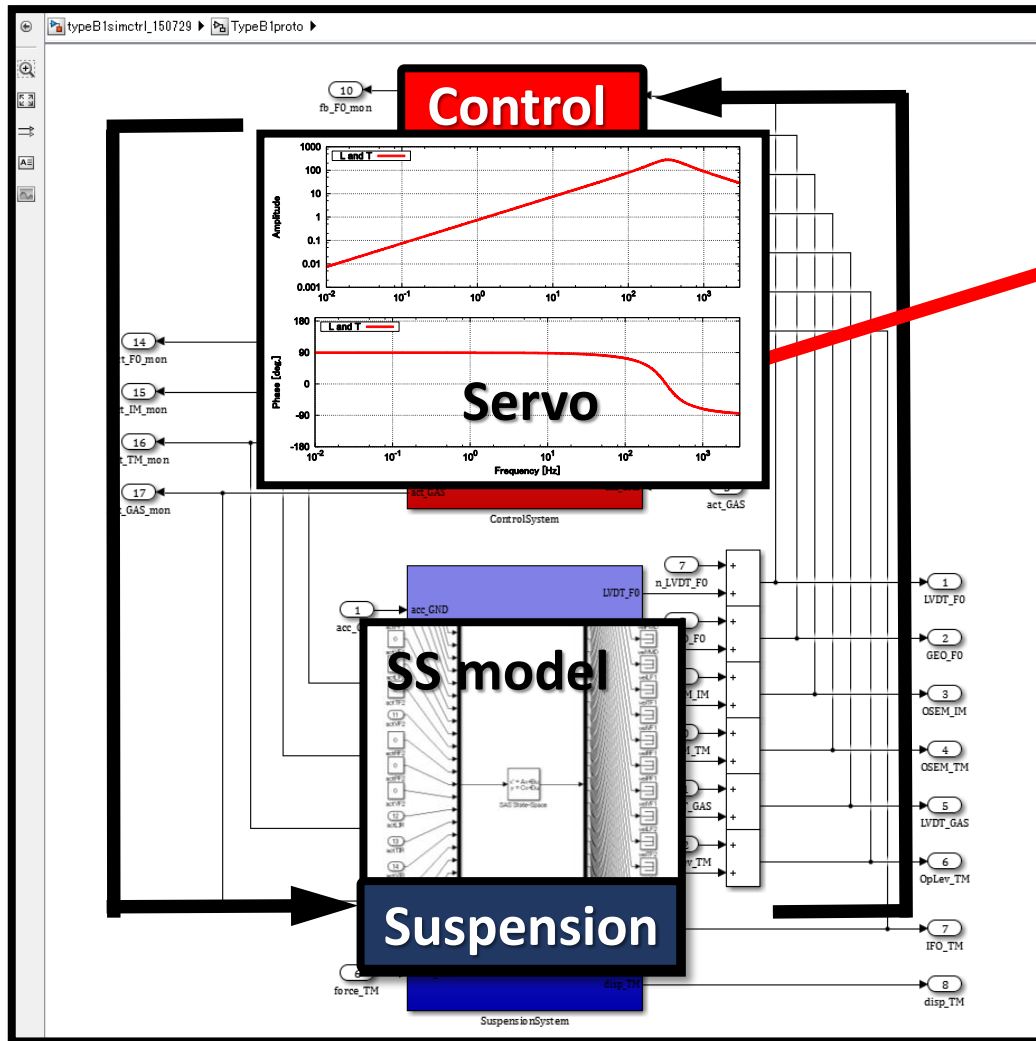
Open loop / Closed loop TF

Q factor

Sensor noise coupling

Mirror angular fluctuation

# Modeling tools : Active model



IM servo filters using OSEMs (displacement sensor)

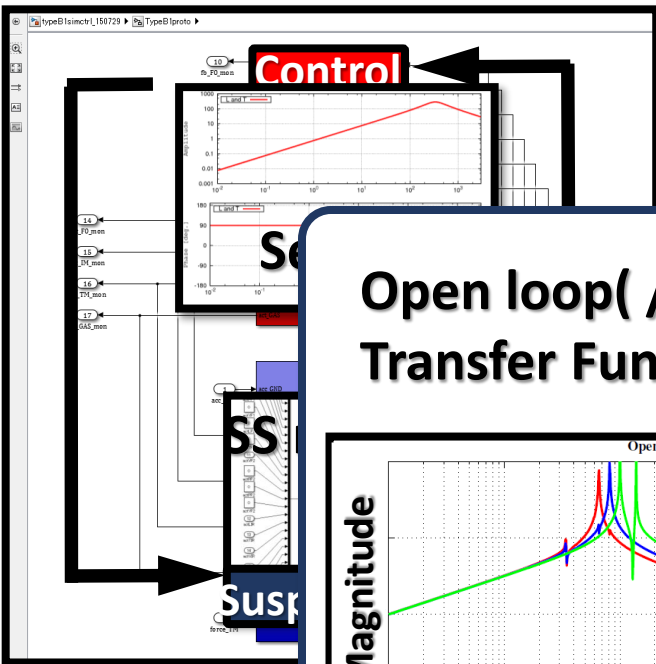
Viscous damping filter using displacement

$$\rightarrow \propto f$$

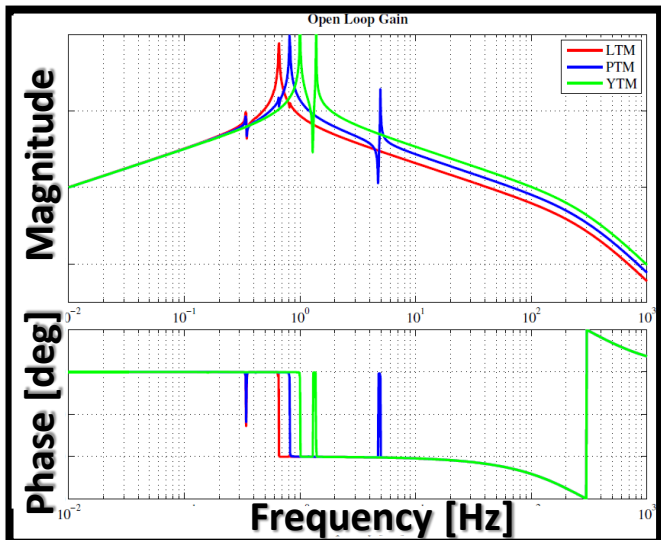
Infinite gain at  $f \rightarrow \infty$  is not applicable!

**→ Need to add a low-pass filter with cut-off.**

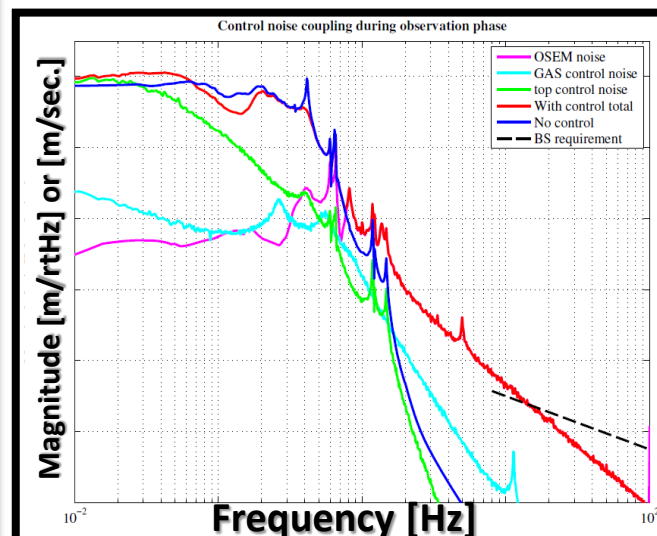
# Modeling tools : Active model



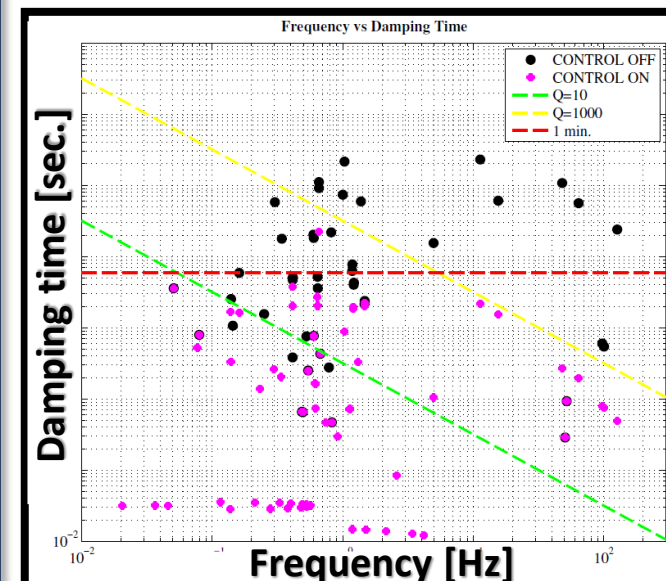
## Open loop( / Closed loop) Transfer Function



## Noise coupling



## Q factor



# Contents

## □ Intro

### □ KAGRA / Suspension Configuration /

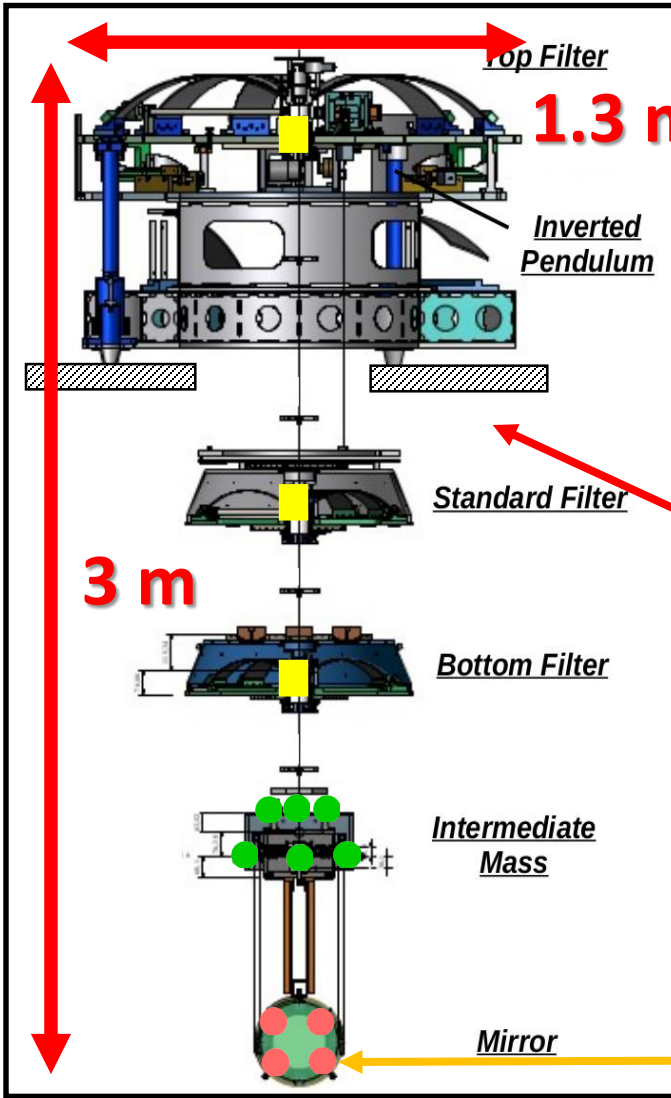
## ❖ Suspension modeling

### □ Modeling tools

### □ Implementation to BS SAS prototype exp.



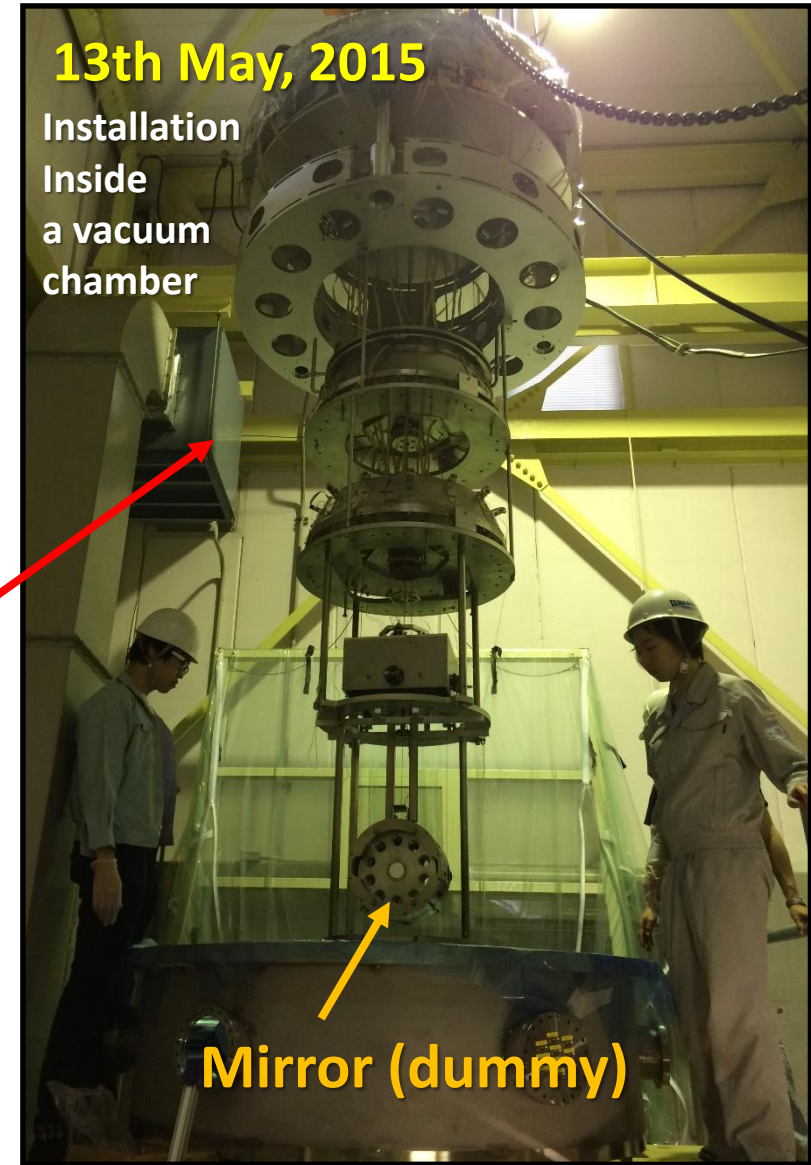
# Implementation to BS SAS prototype exp.



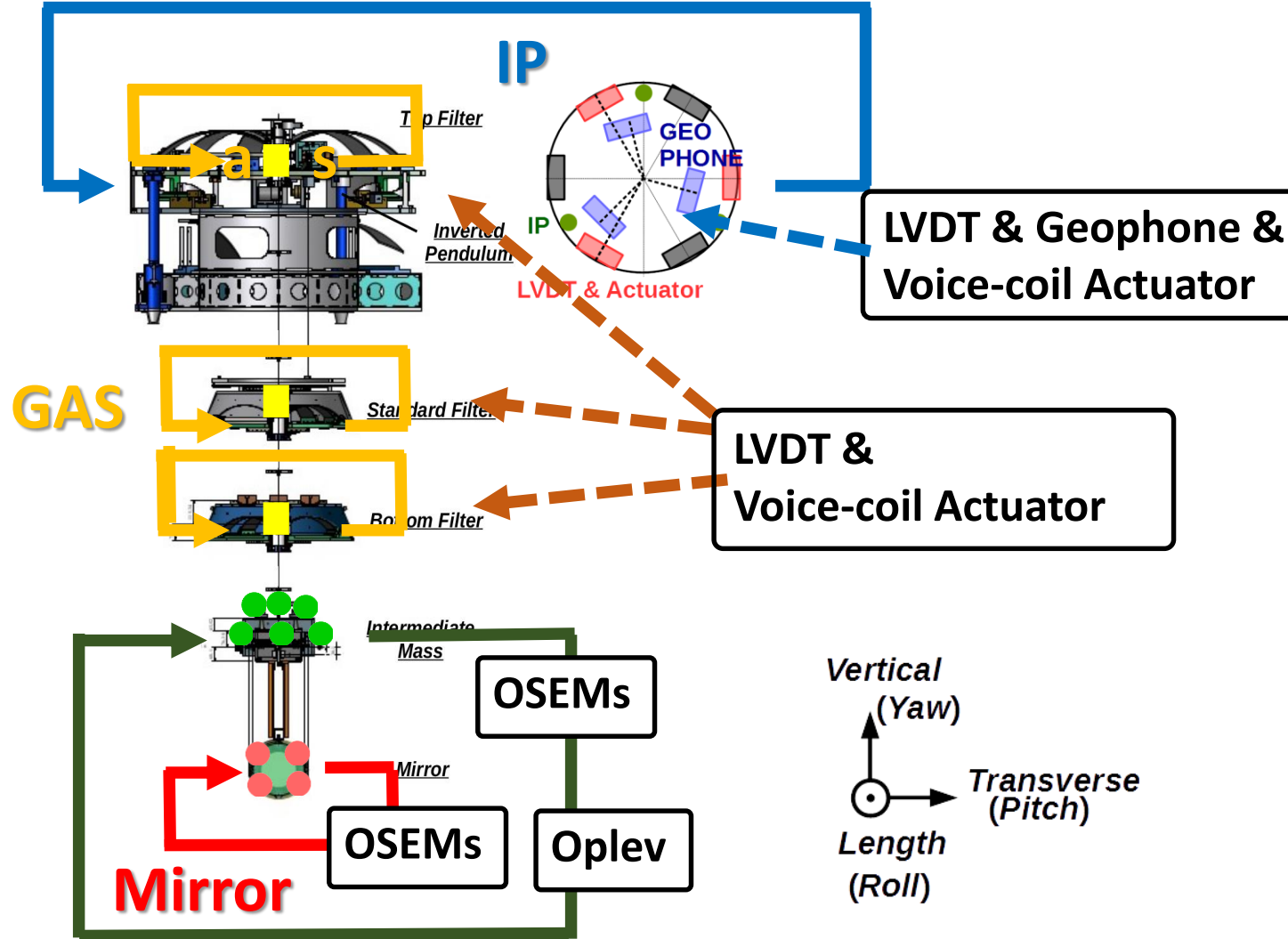
## KAGRA SAS for BS, SR

5th stage pendulum with IP, 3 GAS filters

Mirror



# ❖ Implementation to BS SAS prototype exp. ; Local control overview



## IP servo :

DC position control (L, T)  
Thermal drift control  
Pendulum mode damping

## GAS filter servo

DC position control (V)  
Thermal drift control  
GAS filter mode damping

## Payload servo :

DC alignment control  
Pendulum / rotational mode damping

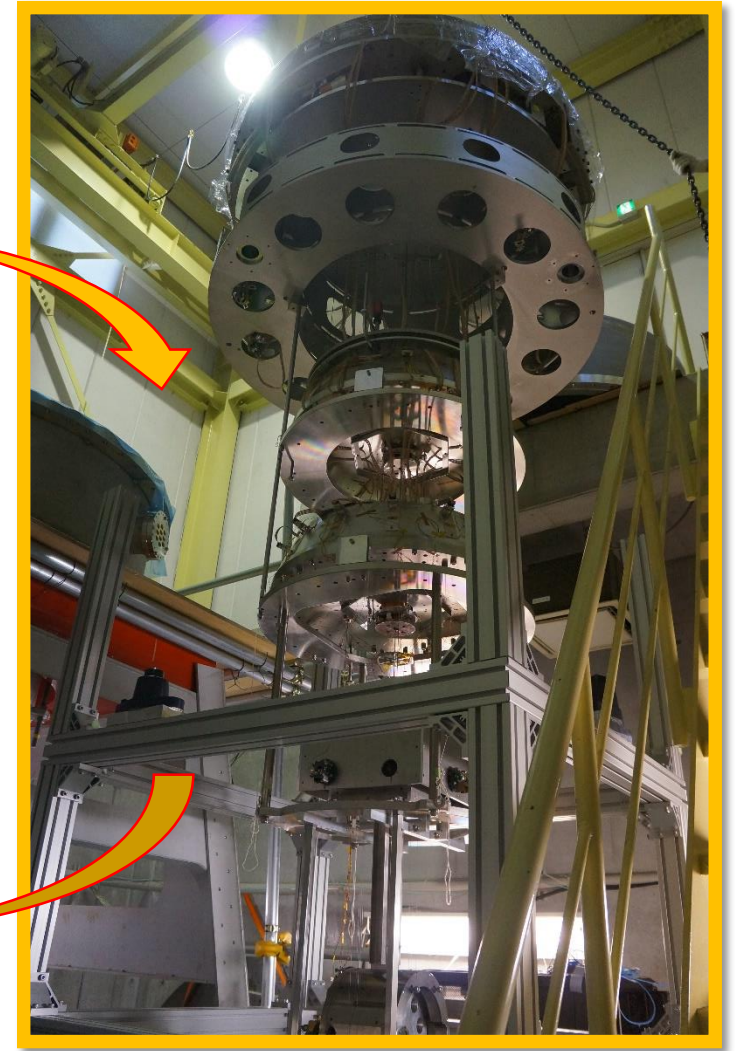
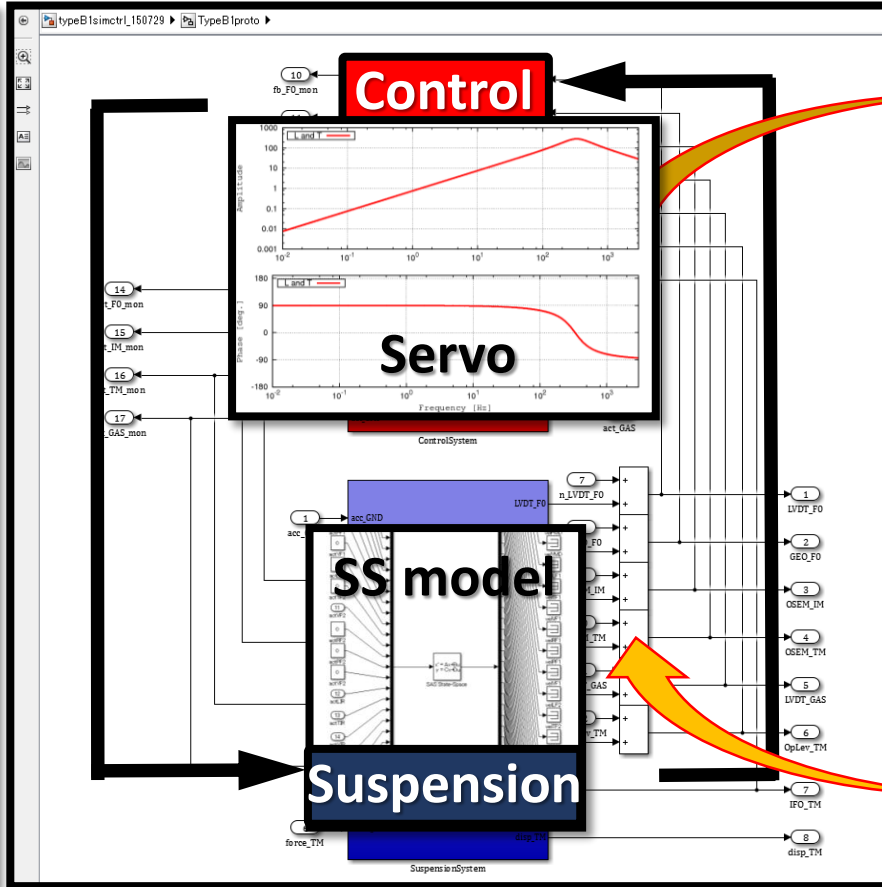
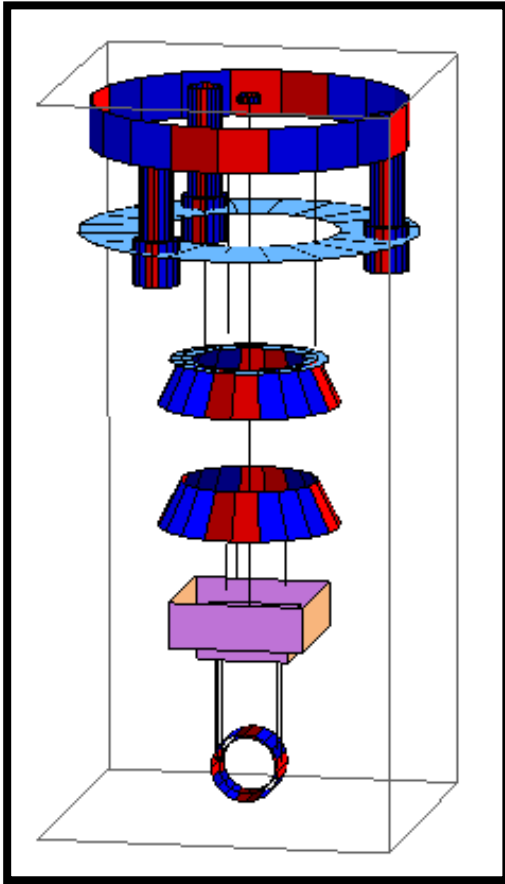
## ❖ Implementation to BS SAS prototype exp.

### Main flow

1. **Make a model and do simulation** on Simulink, Mathematica (and FEM)  
↓
2. **Assemble** suspension system with Frequency response test  
↓
3. **Tune servo filters** on Simulink from measured Transfer Functions  
↓
4. **implement** the servo filters to the actual system  
↓
5. **Test SAS performances**

# ❖ Implementation to BS SAS prototype exp.

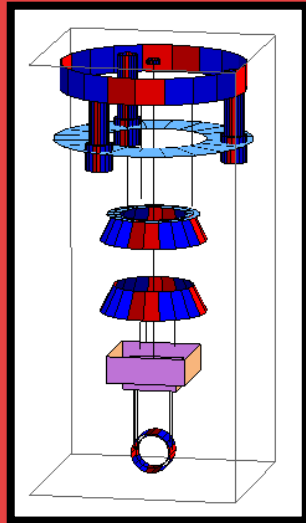
**How was the simulation used in the experiment ?**



# ❖ Implementation to BS SAS prototype exp.

## Visual part

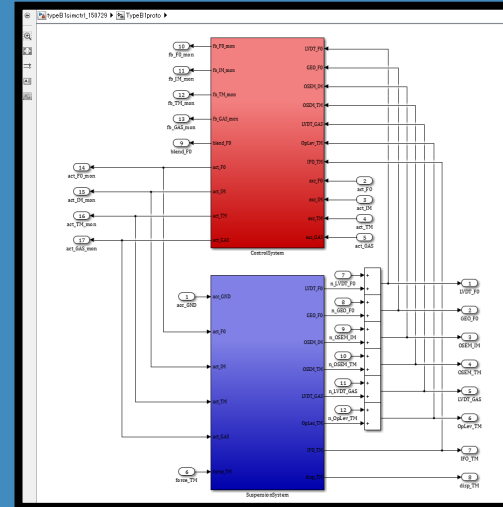
**SUMCON**  
spension odel structor



VS.

## Numerical part

**MATLAB**  
SIMULINK



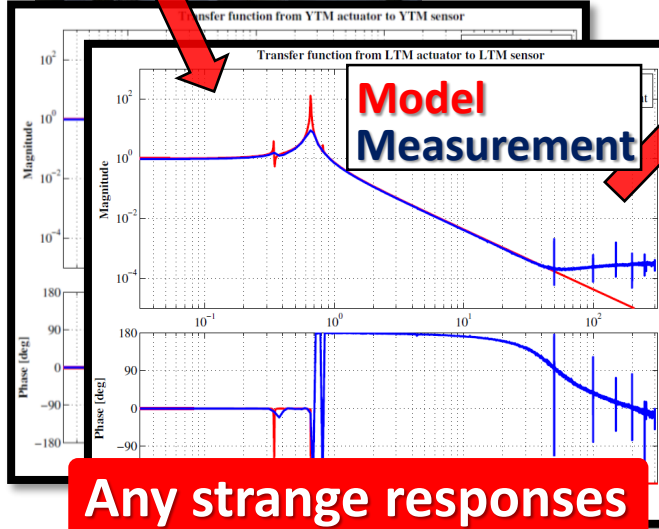
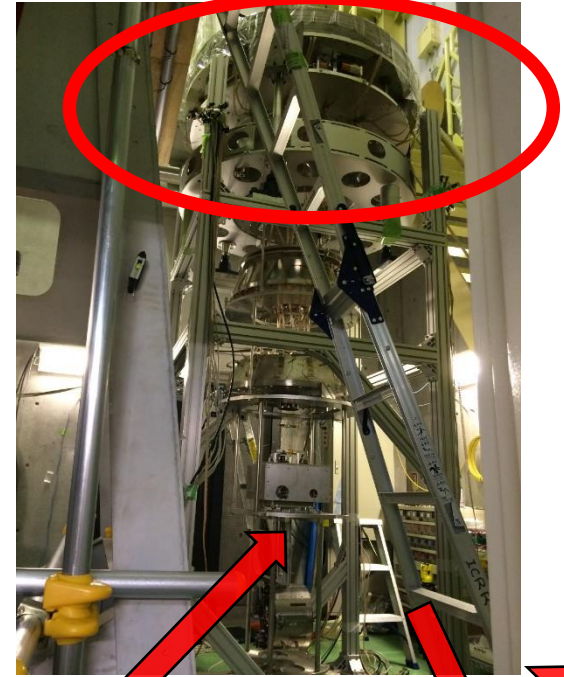
## ❖ Implementation to BS SAS prototype exp.

### Main flow

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↓
4. **implement** the servo filters to the actual system  
↓
5. **Test SAS performances**

# ❖ Implementation to BS SAS prototype exp.

In assembly



No

No

No

Any strange responses against the model ?

Any strange responses against the model ?

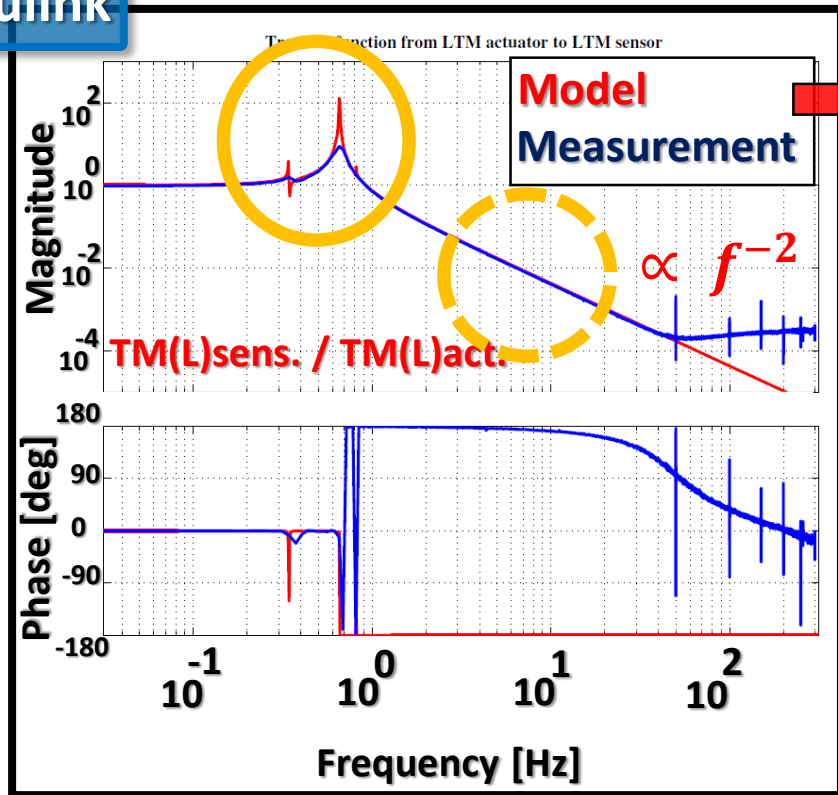
Any strange responses against the model ?

# ❖ Implementation to BS SAS prototype exp.

In assembly

## Force / Torque transfer function with No controls

Simulink

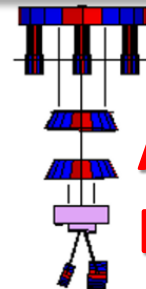


Large discrepancy against the model in  
- resonance frequencies ?  
- Q factor ?

↓ If, Yes

Investigate the reason  
with Eigen mode shape etc.

SUMCON



Any friction?  
Broken parts?



## ❖ Implementation to BS SAS prototype exp.

### Main flow

1. **Make a model and do simulation** on Simulink, Mathematica (and FEM)



2. **Assemble** suspension system with Frequency response test



3. **Tune servo filters** on Simulink from measured Transfer Functions



4. **implement** the servo filters to the actual system

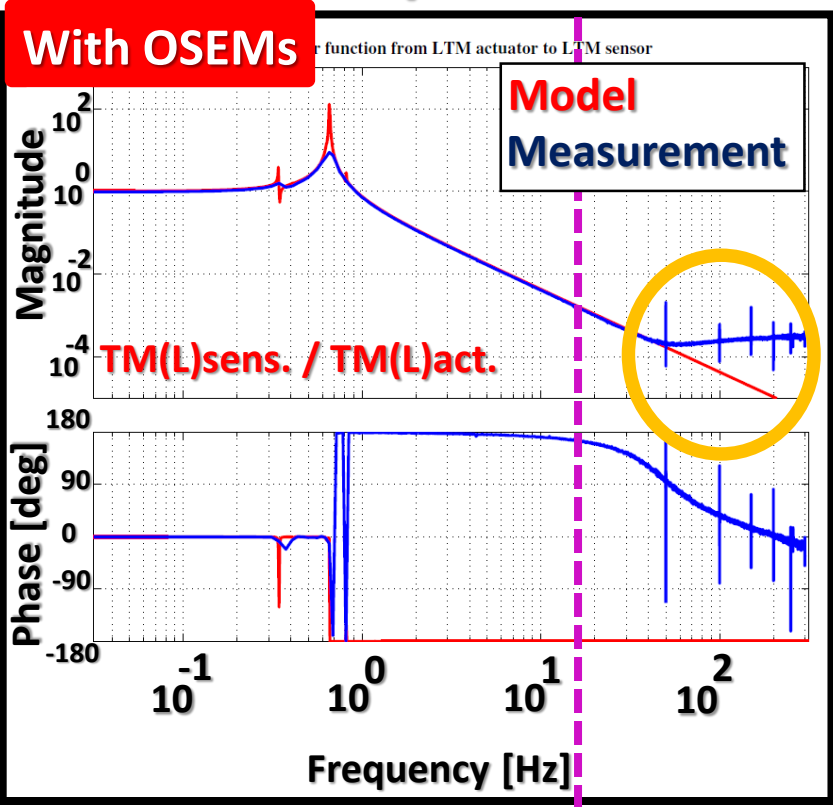


5. **Test SAS performances**

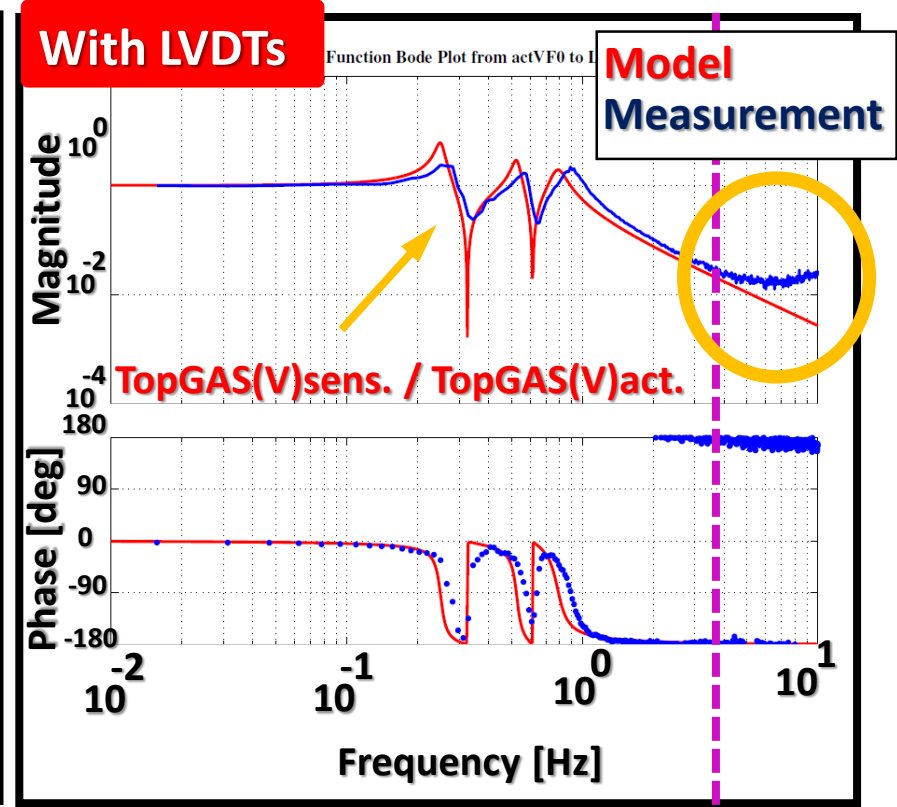
# Implementation to BS SAS prototype exp.

## In tuning servo filters

### Force / Torque transfer function



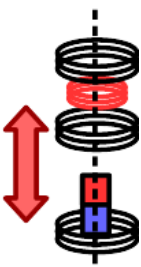
Correspond to the Model



Correspond to the Model

### Discrepancies

- EM coupling
- OSEM : above 5 Hz
- LVDT : above 50 Hz



- Resonance frequency
- Q factor
- Hanging condition
- Asymmetry in IP stiffness
- Ham noise
- wire violin mode

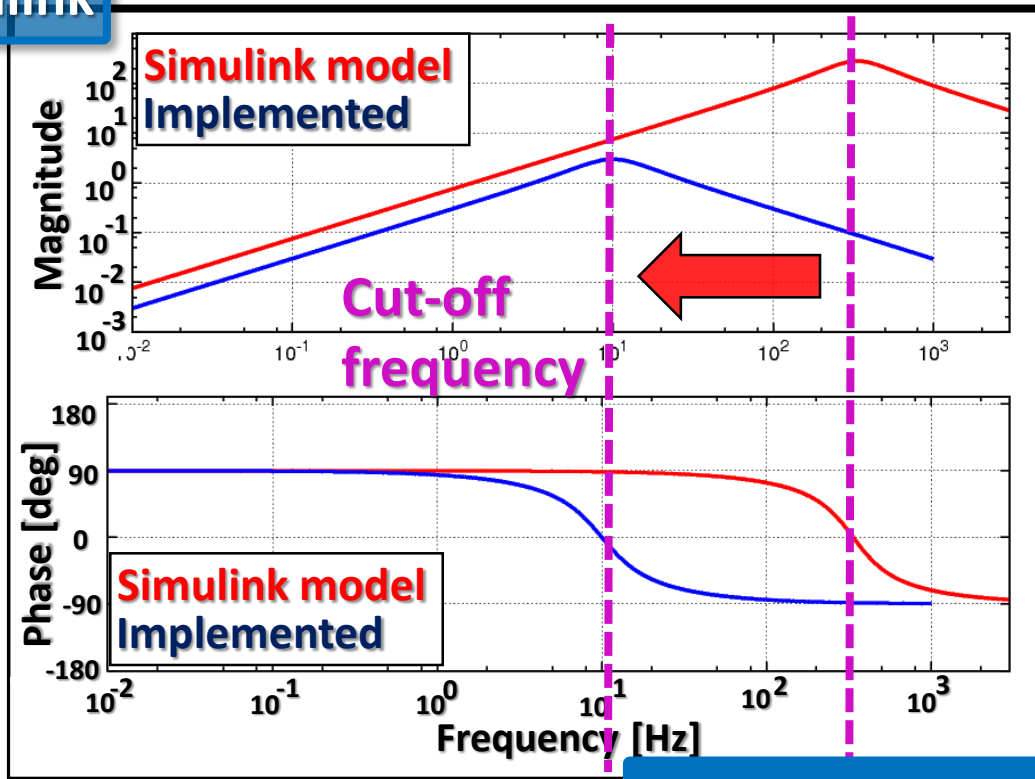
# ❖ Implementation to BS SAS prototype exp.

In tuning servo filters

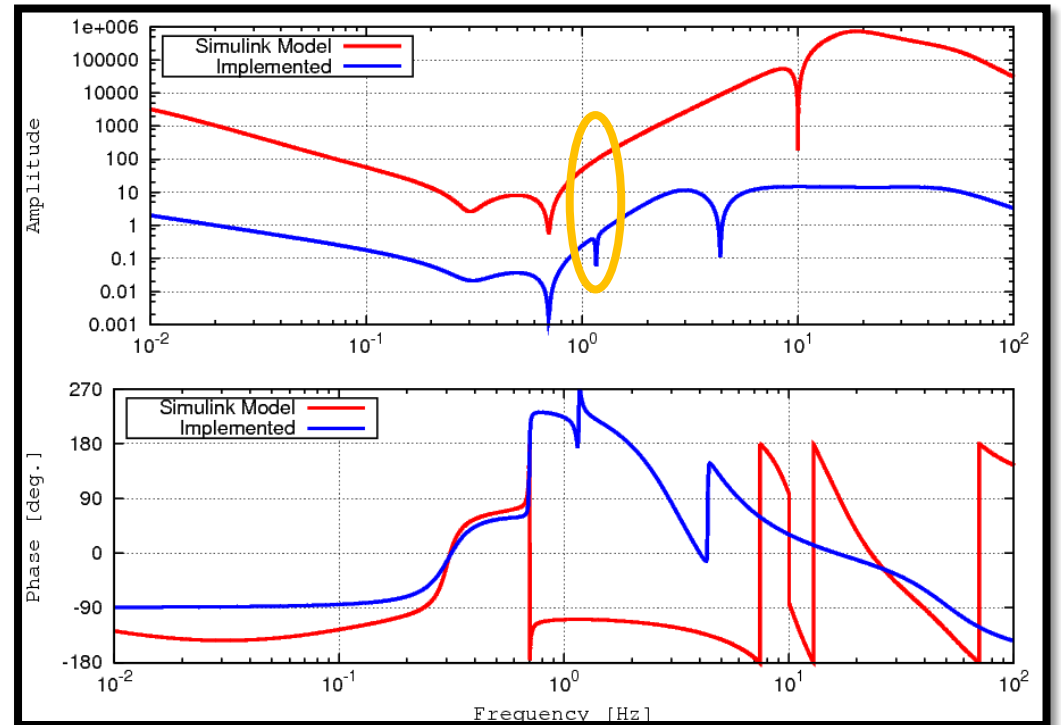
Change cut-off frequency /

Add notch filter(, if necessary)  
at frequency easy to oscillate

Simulink



(For IM L and T)



## ❖ Implementation to BS SAS prototype exp.

### Main flow

1. **Make a model and do simulation** on Simulink, Mathematica (and FEM)



2. **Assemble** suspension system with Frequency response test



3. **Tune servo filters** on Simulink from measured Transfer Functions



4. **implement** the servo filters to the actual system



5. **Test SAS performances**

## ❖ Implementation to BS SAS prototype exp.

### In testing SAS performances

- Mechanical response test

- Damping control performance test

- Long term stability test

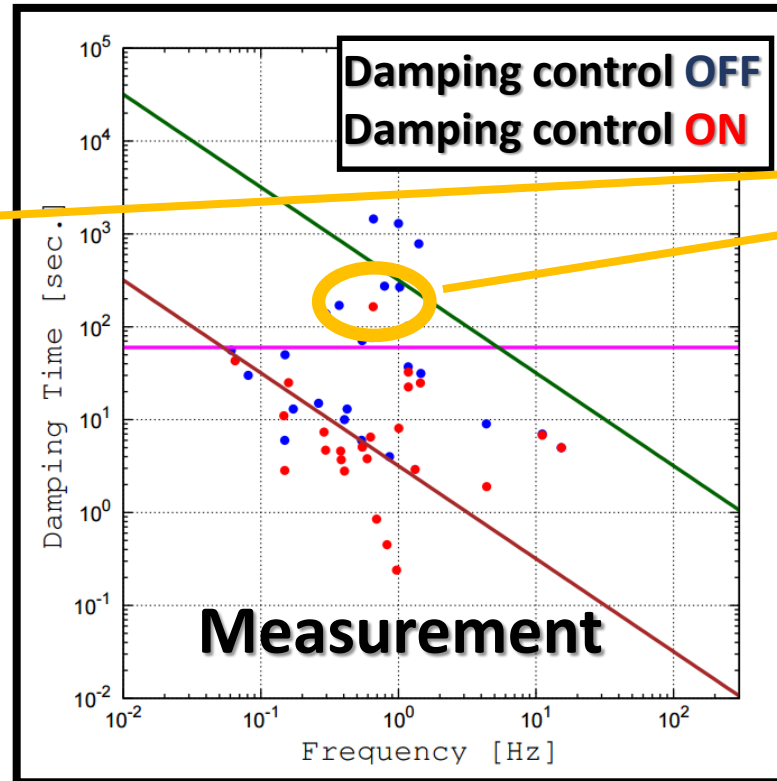
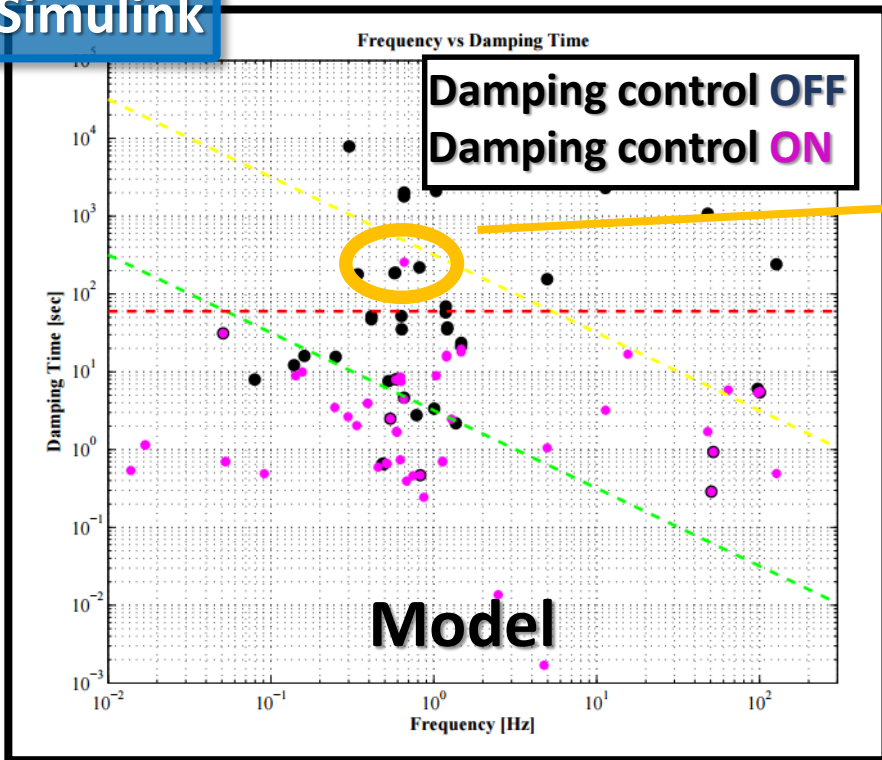
→ For Calming the SAS down

# Implementation to BS SAS prototype exp.

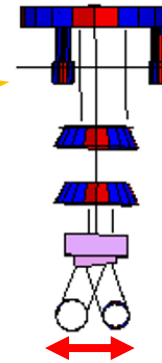
In testing SAS performances

## Damping control performance test for Calming the SAS down

Simulink



SUMCON

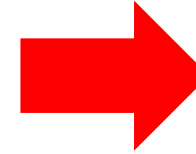


Lock acquisition failure doesn't contribute to this mode.

# Summary

❖ 2 modeling tools are used in KAGRA SAS :

- SUMCON for visual confirming
- Simulink for numerical confirming



**Using both of them  
Is useful !**

❖ We implemented those tools into actual SAS, for the first time;

- at low frequency → Rigid body model could explain actual system
- control digital system for the prototype worked well.

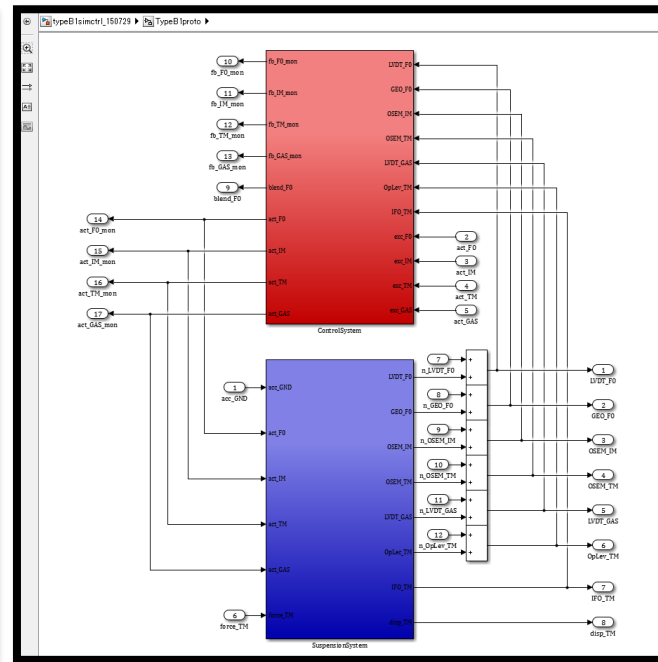
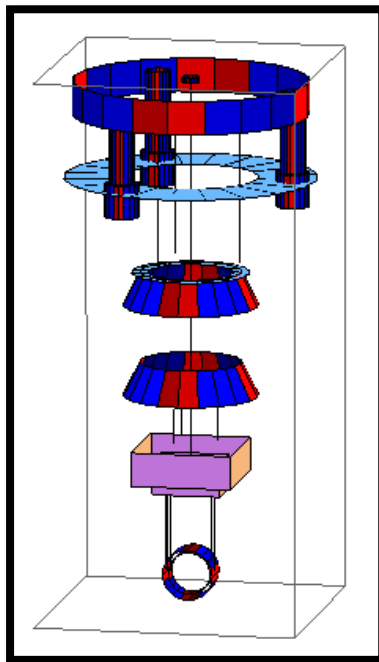
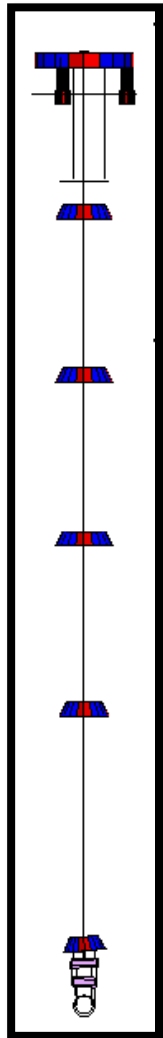
## Next step

- ❖ build SAS for iKAGRA using those tools.
- ❖ Construct current bKAGRA TM SAS model.

# You can use the modeling tools : SUMCON and Simulink !

<http://gwdoc.icrr.u-tokyo.ac.jp/cgi-bin/DocDB/ShowDocument?docid=3729>

<http://gwdoc.icrr.u-tokyo.ac.jp/cgi-bin/DocDB/ShowDocument?docid=3606>



**NOTE : we don't have any manuals, though.**

**If you have any problems, please contact me :  
[yoshinori.fujii AT nao.ac.jp](mailto:yoshinori.fujii@nao.ac.jp)**



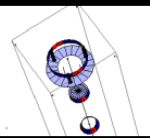
# Thank you for your attention.

# Back up

# Water is now preparing to spring,,,?



# ❖ Modeling tools : Mechanical model



## Main flow

### 1. Express

$U(x)$  : potential energy  
 $F(x, \dot{x})$  : dissipation function  
 $T(x, \dot{x})$  : kinetic energy

### 2. Find $x_e$ : equilibrium position

$$\left. \frac{\partial U}{\partial x_i} \right|_{x=x_e} = 0$$

( for each  $U, F, T$  )

### 3. Calculate matrix

$$K : K_{ij} = \left. \frac{\partial^2 U}{\partial x_i \partial x_j} \right|_{x=x_e} \quad : \text{stiffness matrix}$$
$$C : C_{ij} = \left. \frac{\partial^2 F}{\partial \dot{x}_i \partial \dot{x}_j} \right|_{x=x_e} \quad : \text{damping matrix}$$
$$M : M_{ij} = \left. \frac{\partial^2 T}{\partial \dot{x}_i \partial \dot{x}_j} \right|_{x=x_e} \quad : \text{inertia matrix}$$

### 4. Construct

Linearized Eq of motion

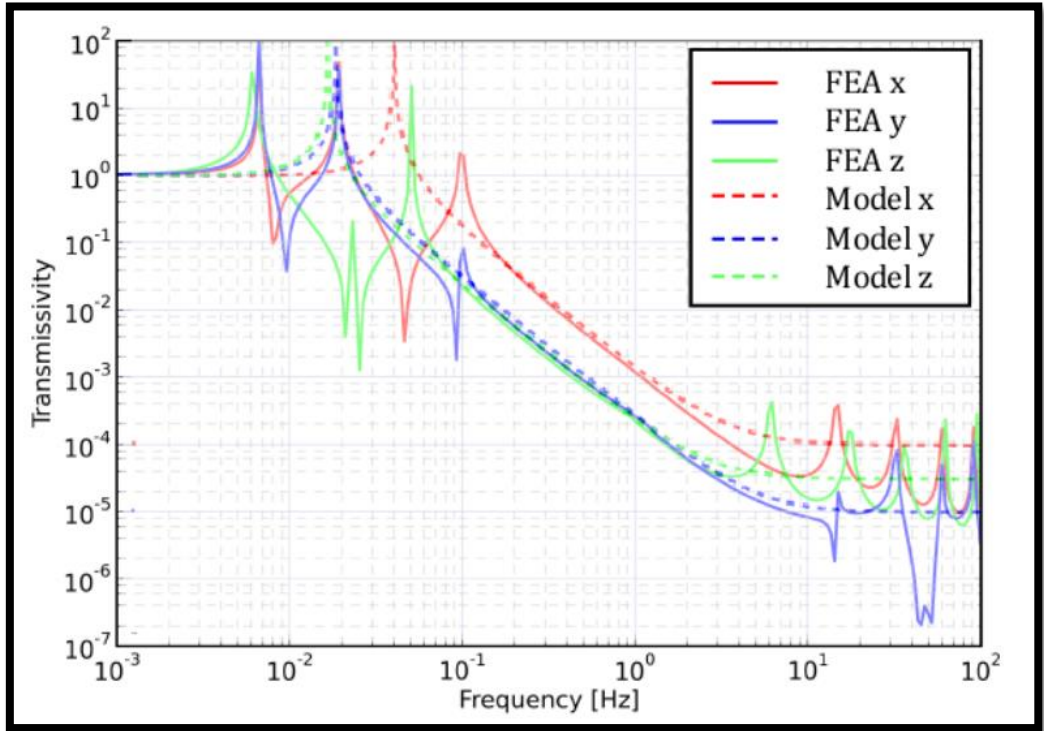
$$K \ddot{x} + C \dot{x} + K(x - x_e) = f$$

$f$  : external force

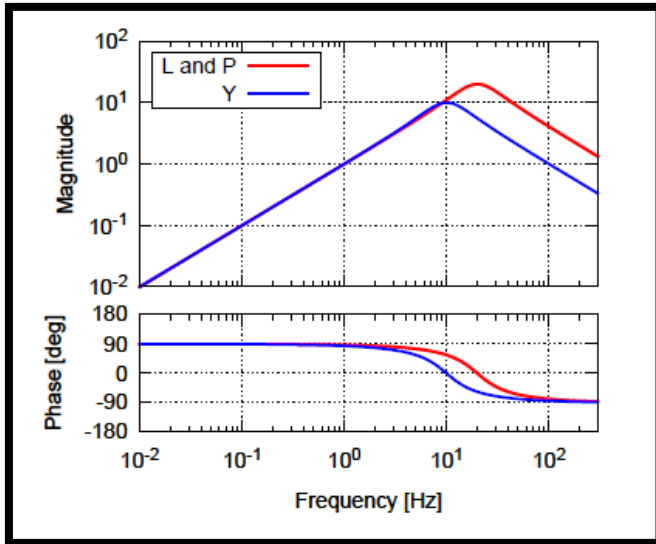
Assuming the vibration is small  
so that we can linearize the system

# ❖ Modeling tools : Mechanical model

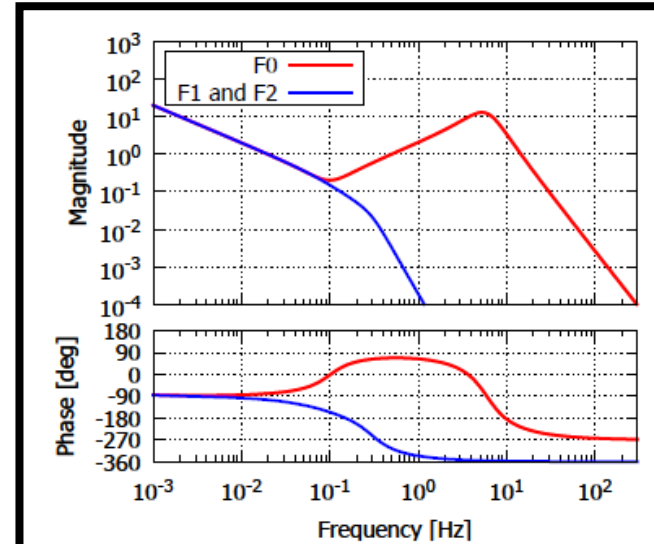
## Heat links



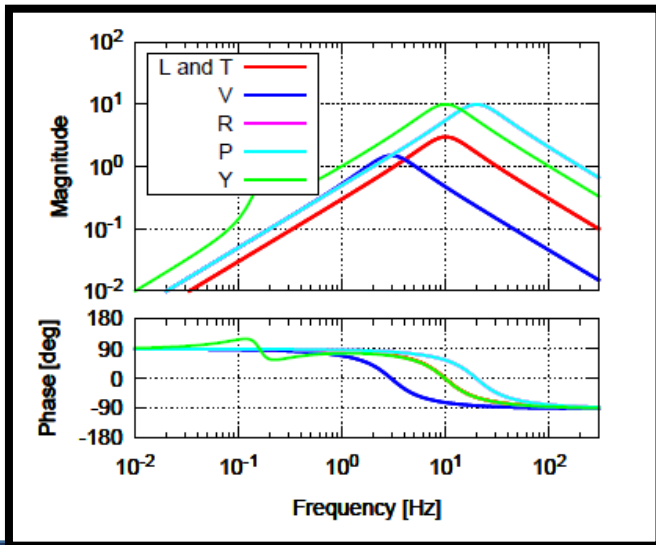
# Modeling tools : actual servo filters for damping



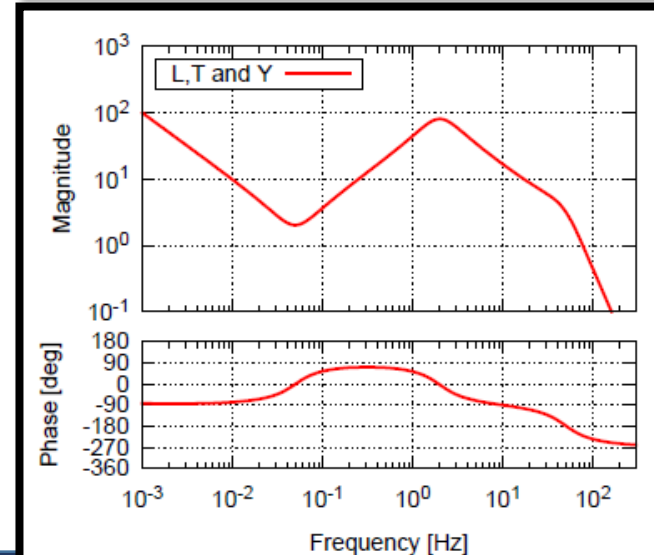
**Servo filter  
For TM OSEM**



**Servo filter  
For GAS filter**

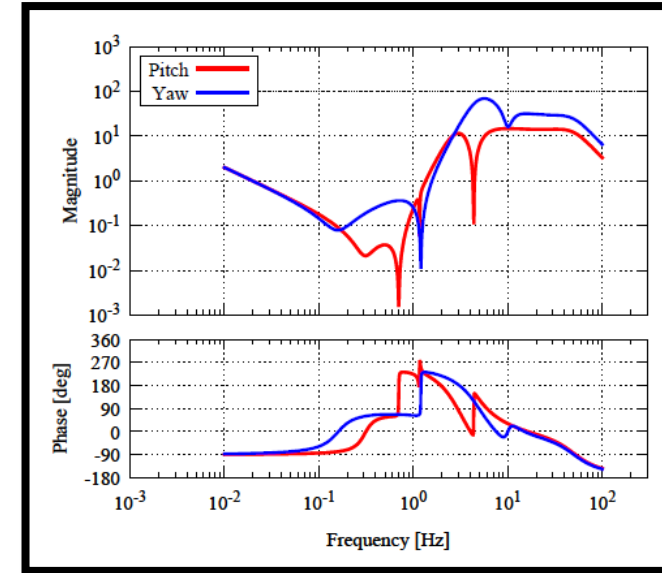
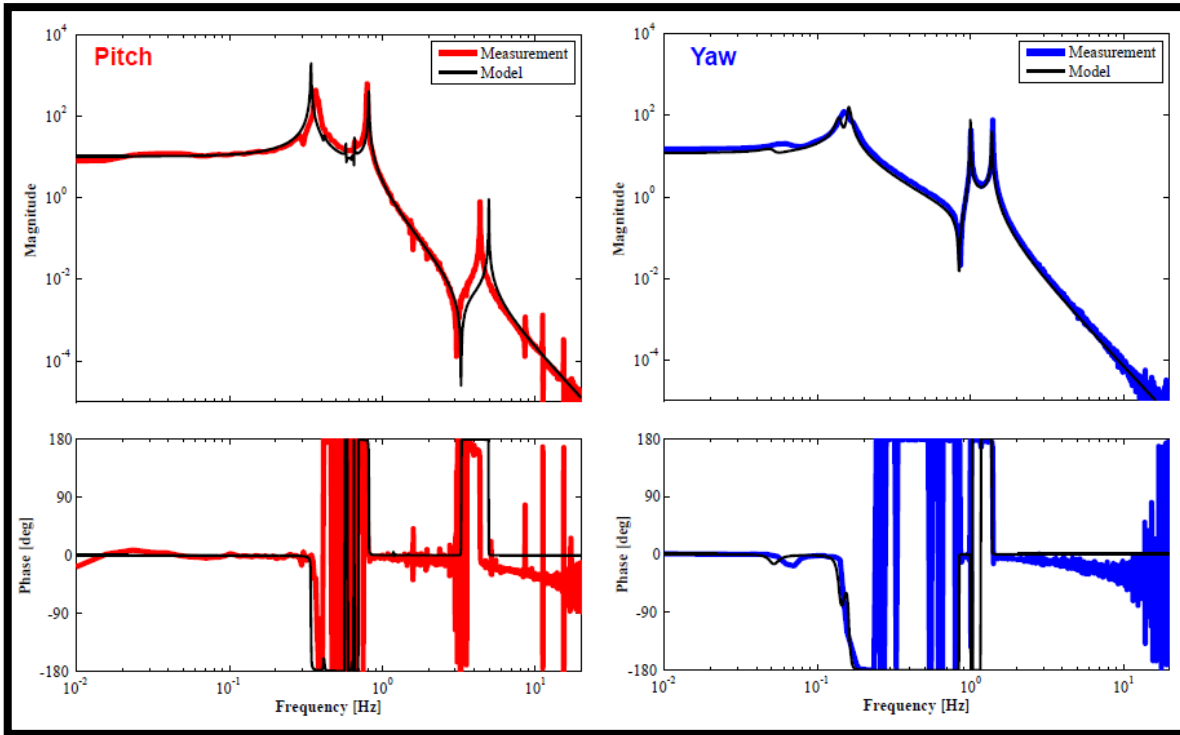


**Servo filter  
For IM OSEM**



**Servo filter  
For IP**

# Modeling tools : actual servo filters for damping



**Servo filter  
for Oplev  
(in front of TM)**

**Transfer function  
from TM act. to Oplev**

# Modeling tools : Mechanical model

For instance,



SUMCON Version:1.32

Step 1. Registrare Rigid Bodies

GND	Name	M [kg]	Ixx [kgm <sup>2</sup> ]	Iyy [kgm <sup>2</sup> ]	Izz [kgm <sup>2</sup> ]	Shape
0	g	0	0	0	0	Doughnut[y]
1-1	F0	554.	97.5	191.4	97.5	Cylinder[y]
1-2	MD	18.	0.717	1.493	0.717	Doughnut[y]
1-3	F1	112.7	4.55	7.87	4.68	TruncatedCone[y]
1-4	F2	106.9	4.01	6.75	4.1	TruncatedCone[y]
1-4	IR	8.3	0.159	0.263	0.17	OpenCuboid[y]
1-4	IM	26.1	0.145	0.247	0.187	OpenCuboid[y]
1-4	RM	13.2	0.19	0.172	0.234	Cylinder[z]
1-4	TM	10.7	0.051	0.051	0.083	Cylinder[z]

Step 2. Set Connection

Set Material Properties

Wire:

Name	Body1	Body2	Material	L [m]	D [mm]
F0-MD-1	F0	MD	Maraging Steel	0.954903	2.
F0-MD-2	F0	MD	Maraging Steel	0.954903	2.
F0-MD-3	F0	MD	Maraging Steel	0.954903	2.
F0-F1-1	F0	F1	Maraging Steel	1.27875	4.5
F1-F2-1	F1	F2	Maraging Steel	0.51305	4.5
F2-IR-1	F2	IR	Maraging Steel	0.354983	2.
F2-IR-2	F2	IR	Maraging Steel	0.354983	2.
F2-IR-3	F2	IR	Maraging Steel	0.354983	2.
F2-IM-1	F2	IM	Maraging Steel	0.584666	2.5
IM-RM-1	IM	RM	Tungsten	0.586829	0.6
IM-RM-2	IM	RM	Tungsten	0.586829	0.6
IM-RM-3	IM	RM	Tungsten	0.586829	0.6

SUMCON in Mathematica

SUMCON Version:1.32

About SUMCON Version Info Refresh

New Model Load Model Save Model TypeB1\*150723\_TypeB1\_Prot.m

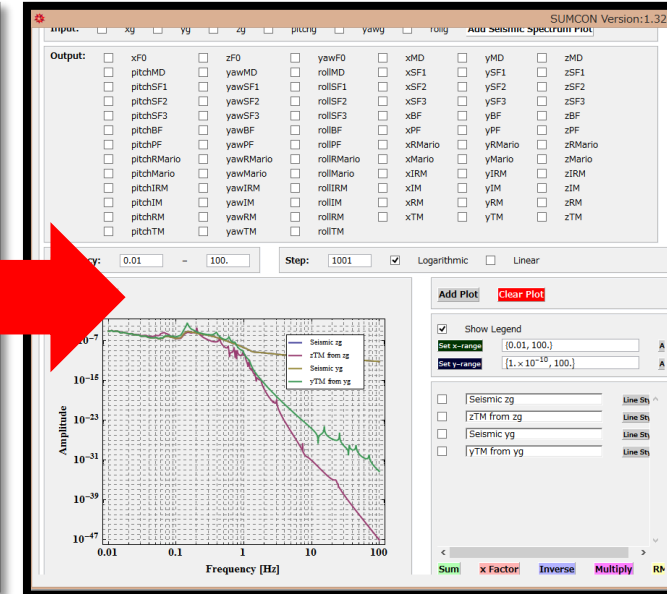
Model Construction Calculation Result Export Model

Model Basic Information

Degrees of Freedom:  
45 State Variables  
Input Variables  
Float Variables

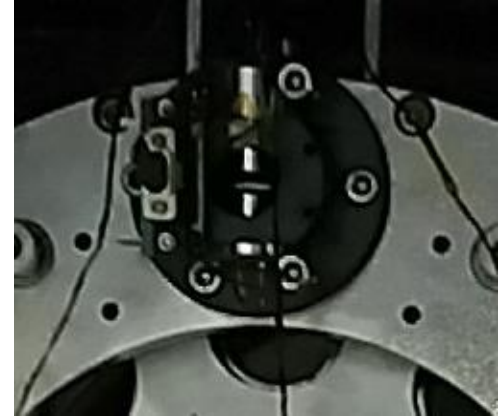
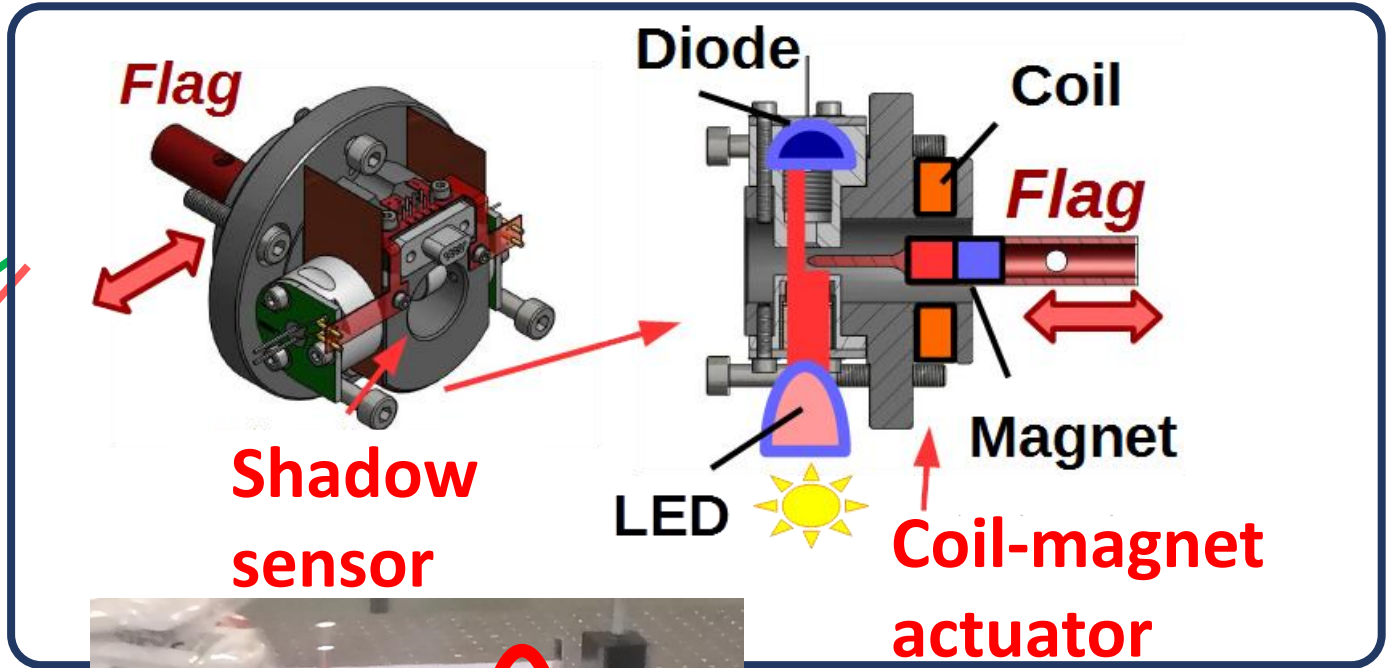
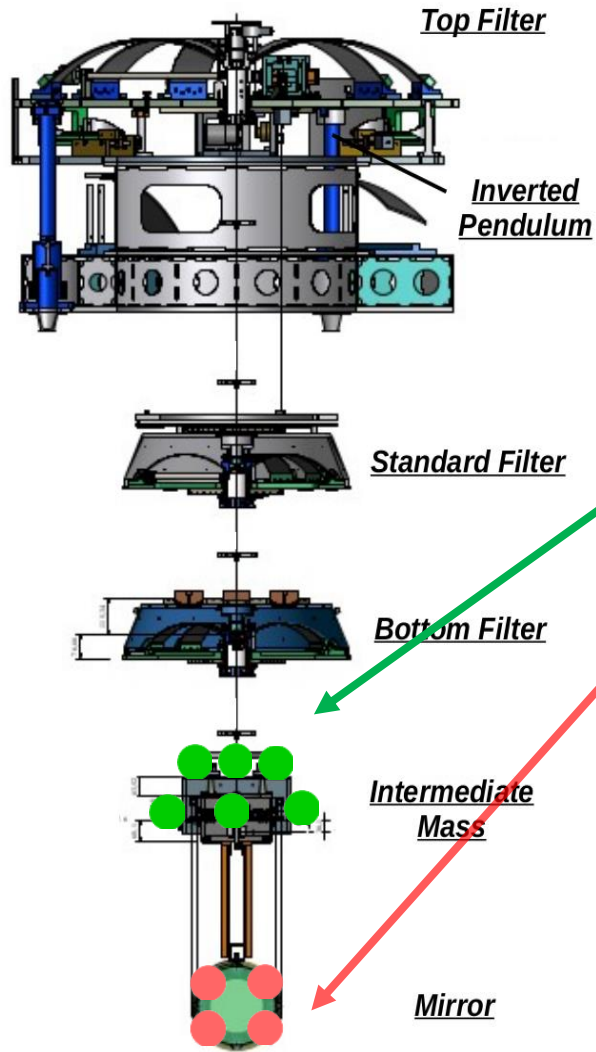
Position:  
yg → 0. zg → 0. pitchg → 0. yawg → 0. rollg → 0.

Equilibrium Point:  
xFO → 0. zFO → 0. yawFO → 0. xMD → 0. yMD → -0.572 zMD → 0.  
pitchMD → 0. yawMD → 0. rollMD → 0. xF1 → 0. yF1 → -0.665 zF1 → 0.  
pitchF1 → 0. yawF1 → 0. rollF1 → 0. xF2 → 0. yF2 → -1.1984 zF2 → 0.  
pitchF2 → 0. yawF2 → 0. rollF2 → 0. xIR → 0. yIR → -1.6936 zIR → 0.  
pitchIR → 0. yawIR → 0. rollIR → 0. xIM → 0. yIM → -1.7699 zIM → 0.  
pitchIM → 0. yawIM → 0. rollIM → 0. xRM → 0. yRM → -2.3569 zRM → 0.  
pitchRM → 0. yawRM → 0. rollRM → 0. xTM → 0. yTM → -2.3569 zTM → 0.  
pitchTM → 0. yawTM → 0. rollTM → 0. hGAS0 → 0. hGAS1 → 0. hGAS2 → 0.





# ❖ BS SAS proto : OSEM Shadow sensor & Coil-magnet actuator unit



# Type B の防振比のsimulation

