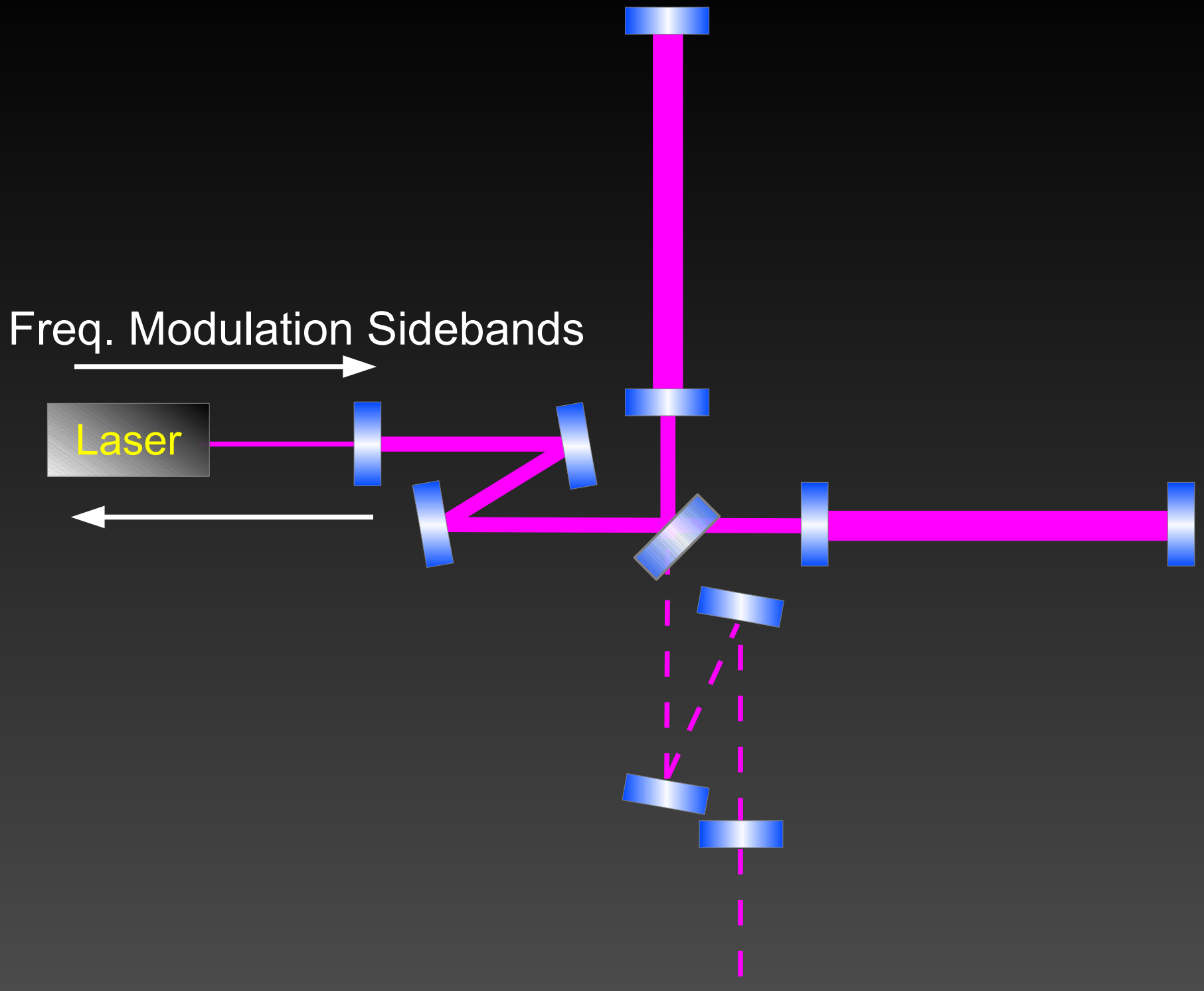
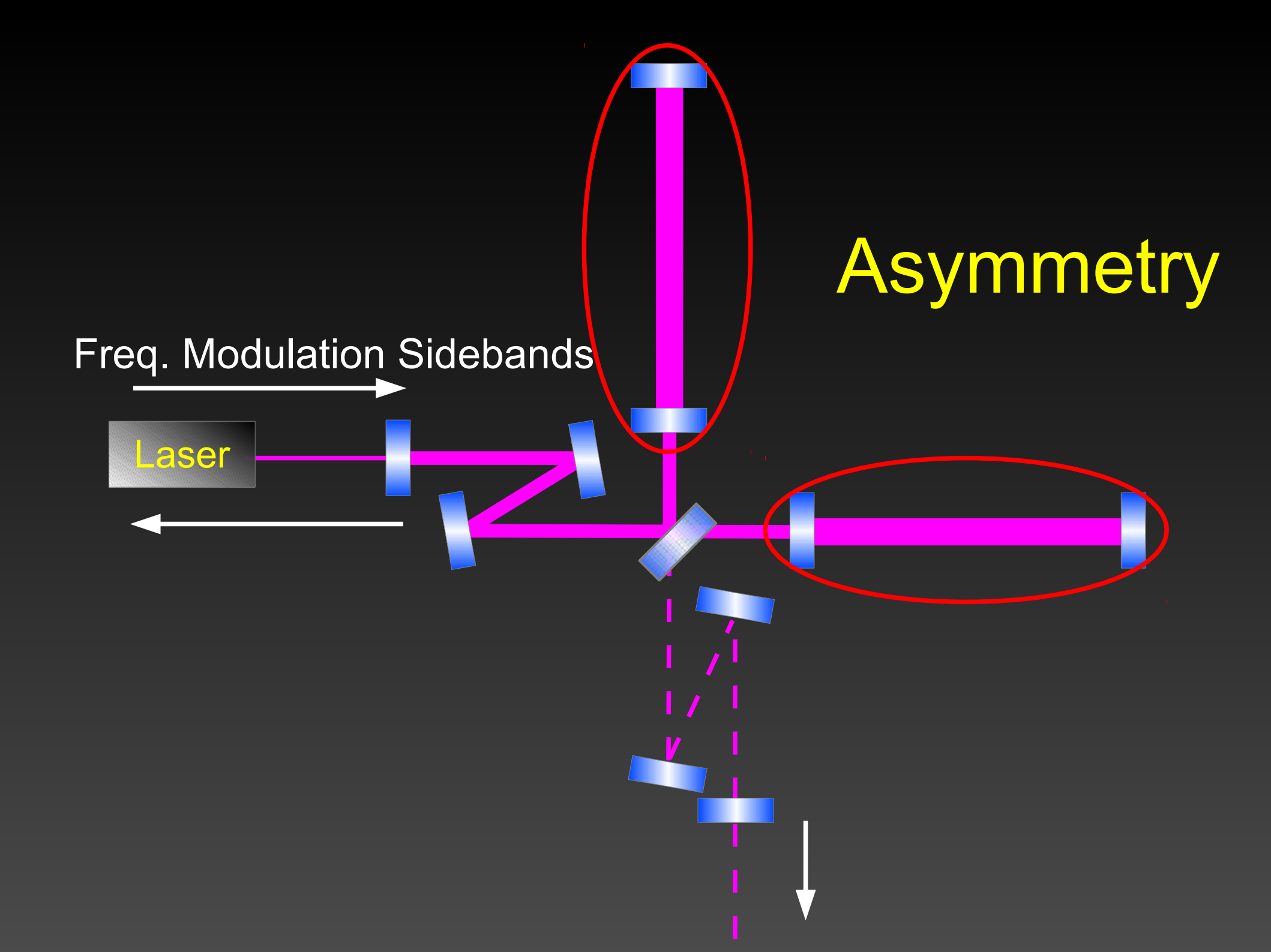
重力波検出器KAGRAの主干渉計開発III

東大理 麻生洋一 他

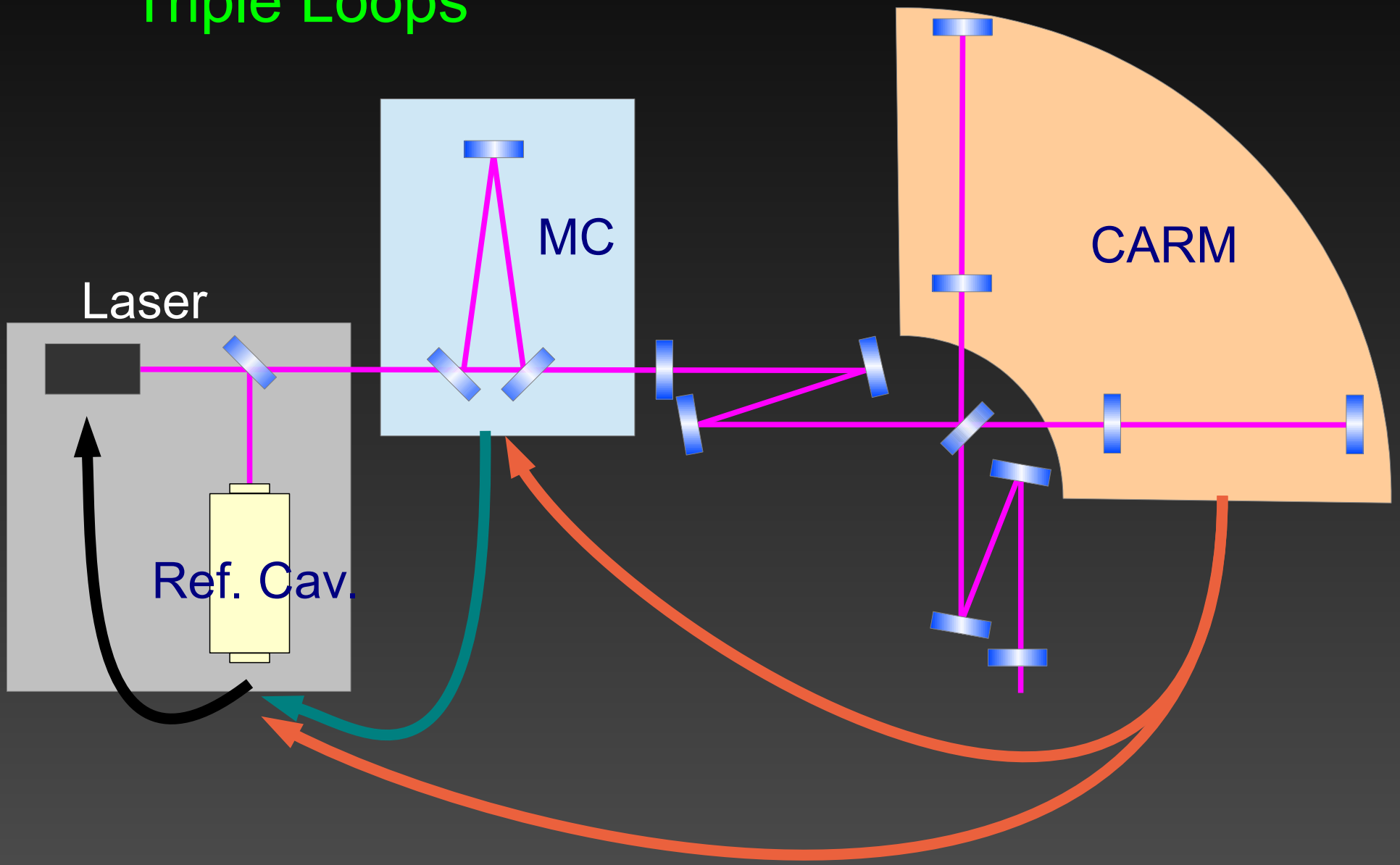
Frequency Stabilization Servo Modeling


Freq. Modulation Sidebands
Laser


Asymmetry
Freq. Modulation Sidebands
Laser

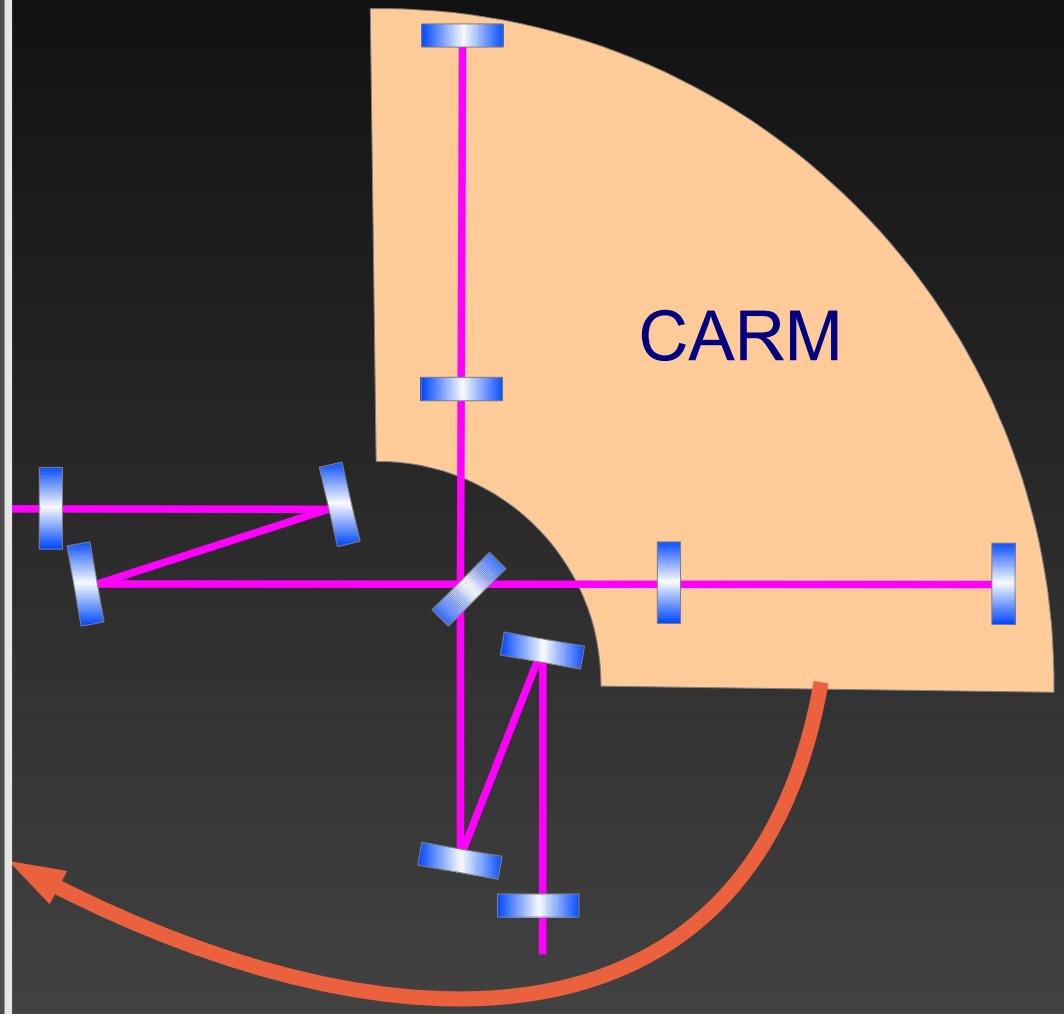
Frequency Stabilization

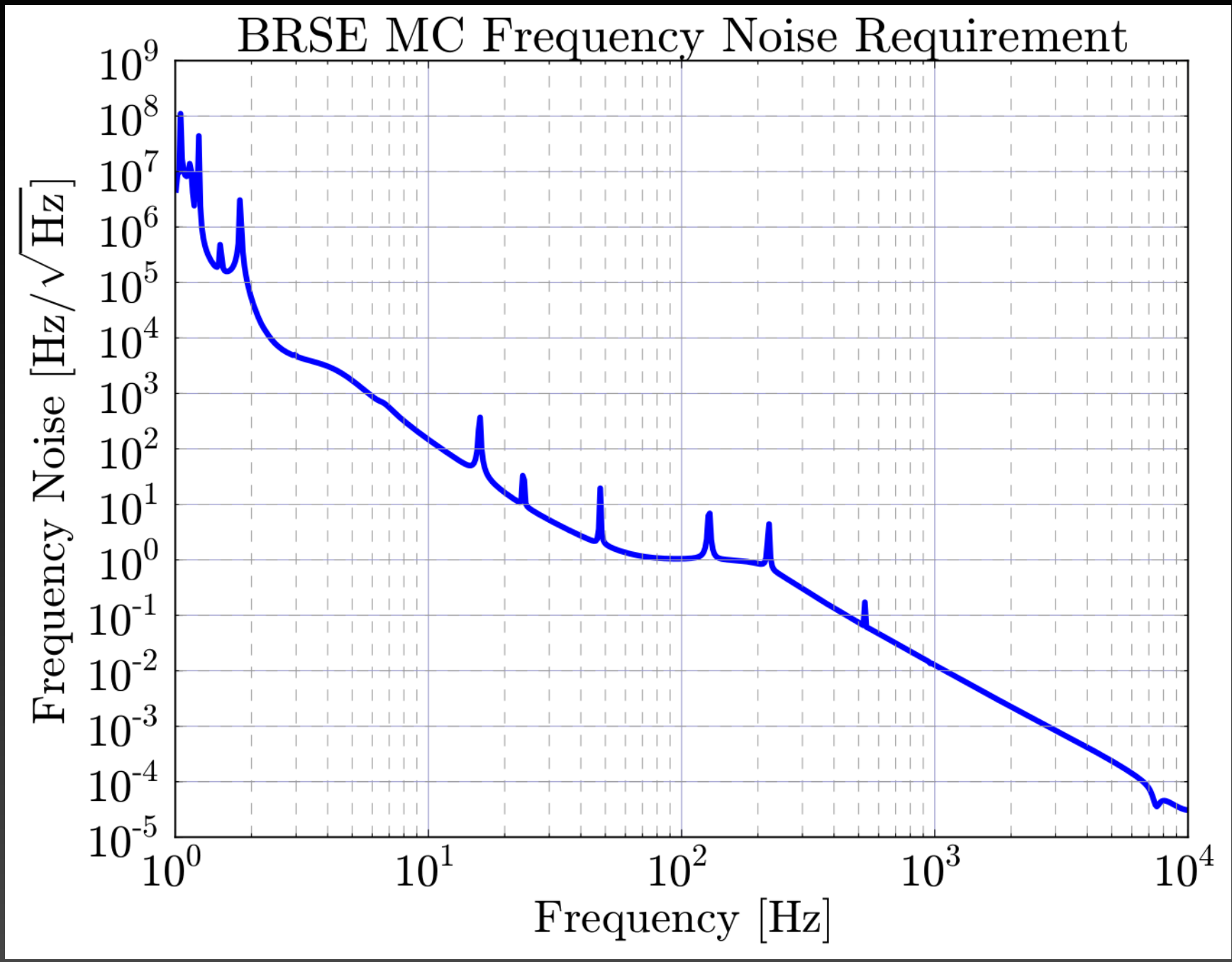
Triple Loops



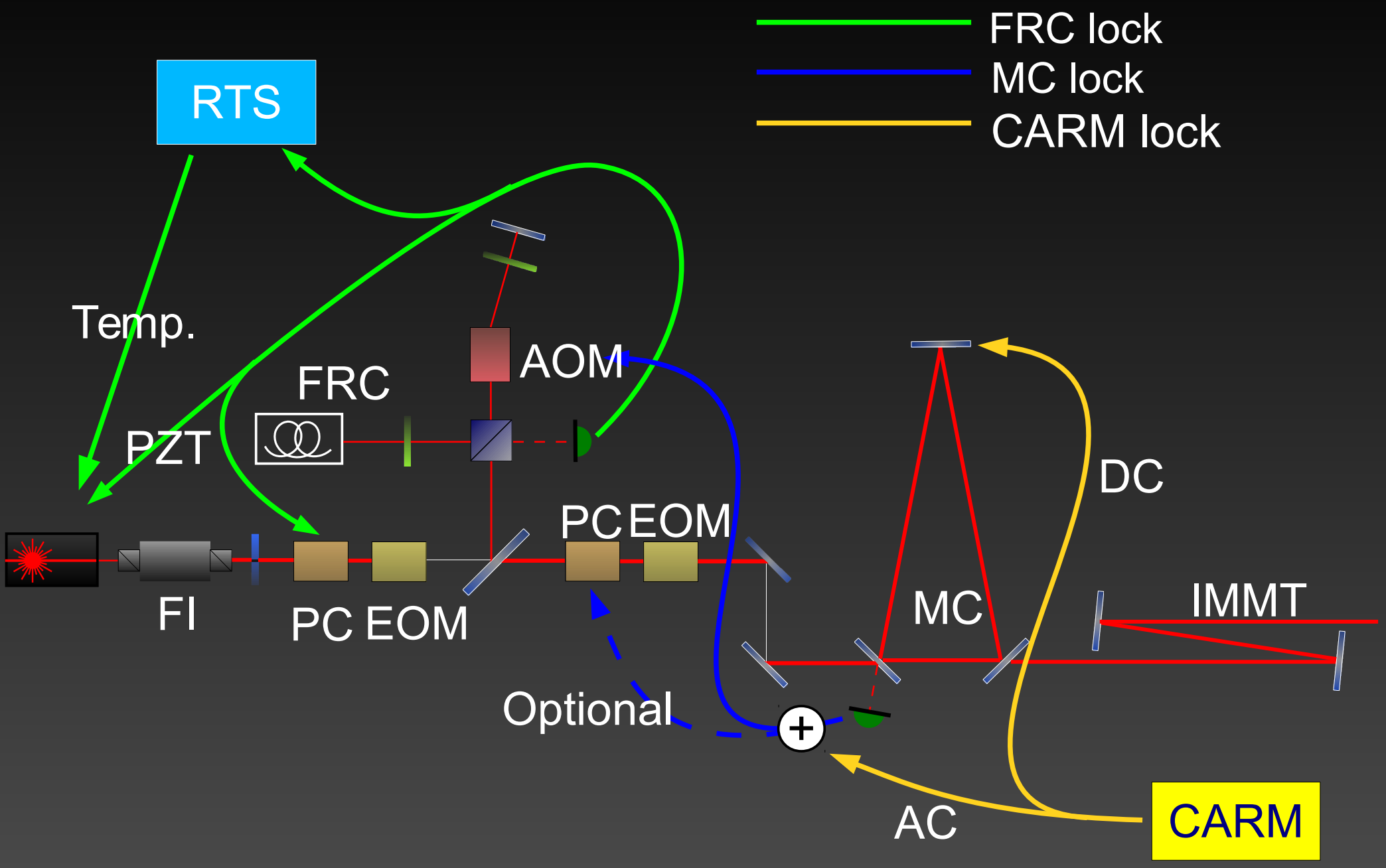
Frequency Stabilization

Black Box



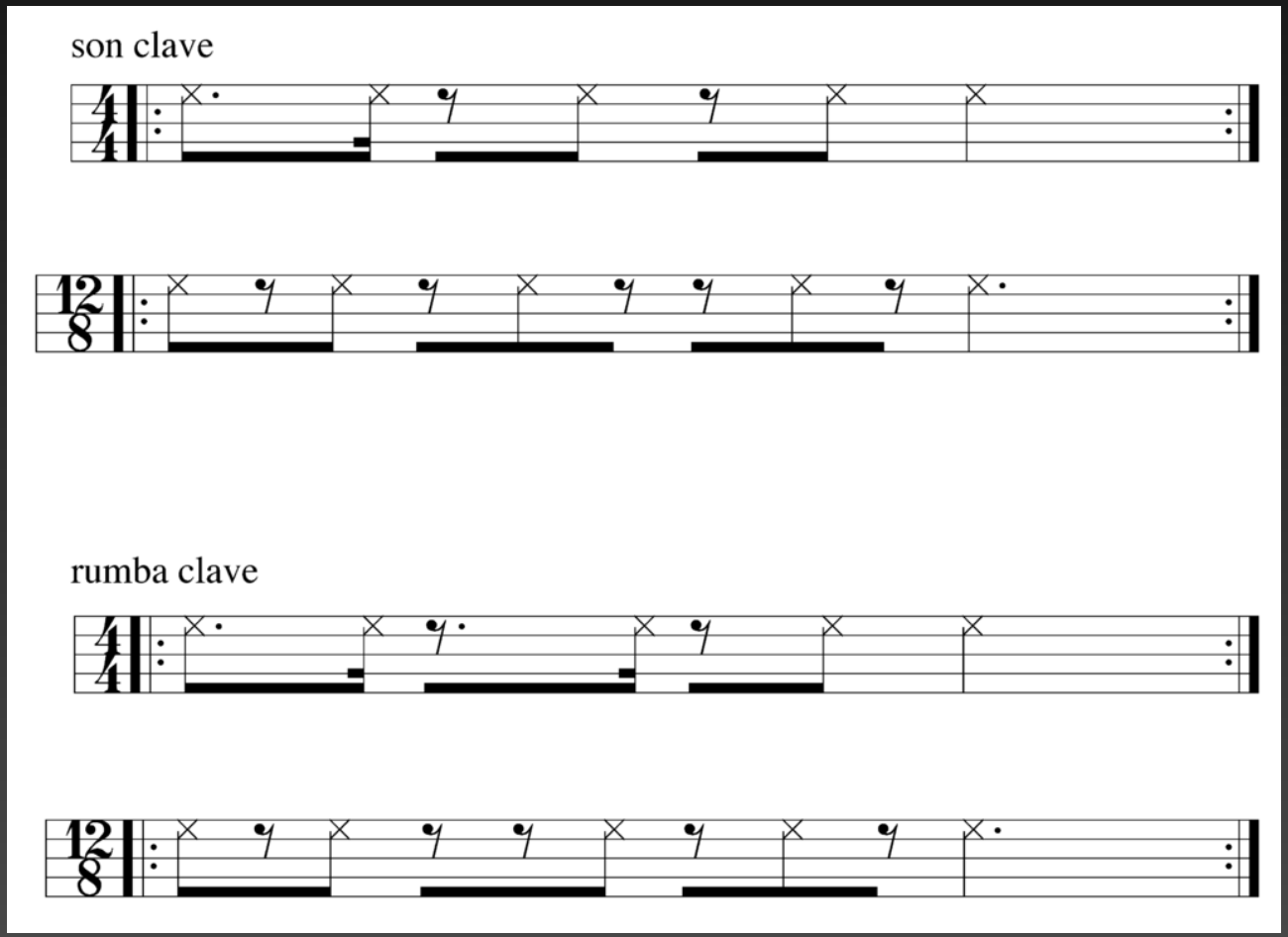

BRSE MC Frequency Noise Requirement
Frequency Noise [Hz/√Hz]
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
Frequency [Hz]

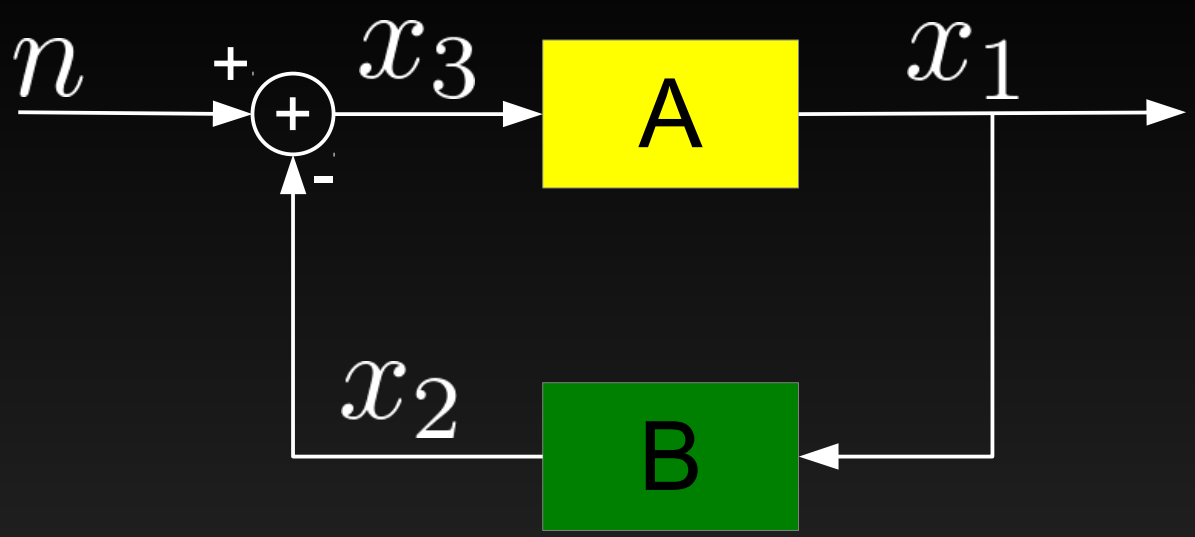
Frequency Stabilization Servo Topology

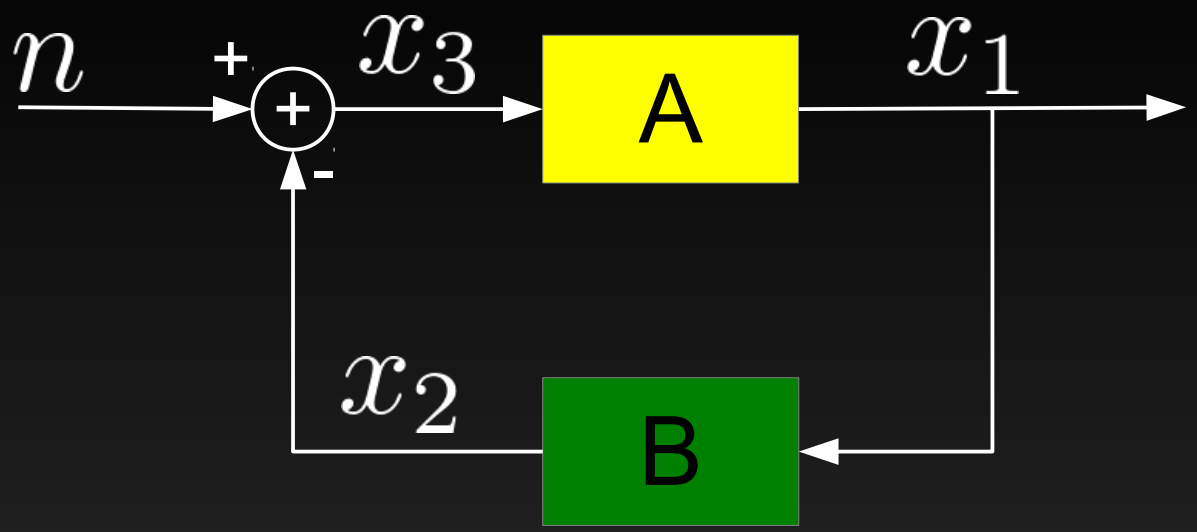


CLAVE:

Control Loop Analysis and Visualization Engine



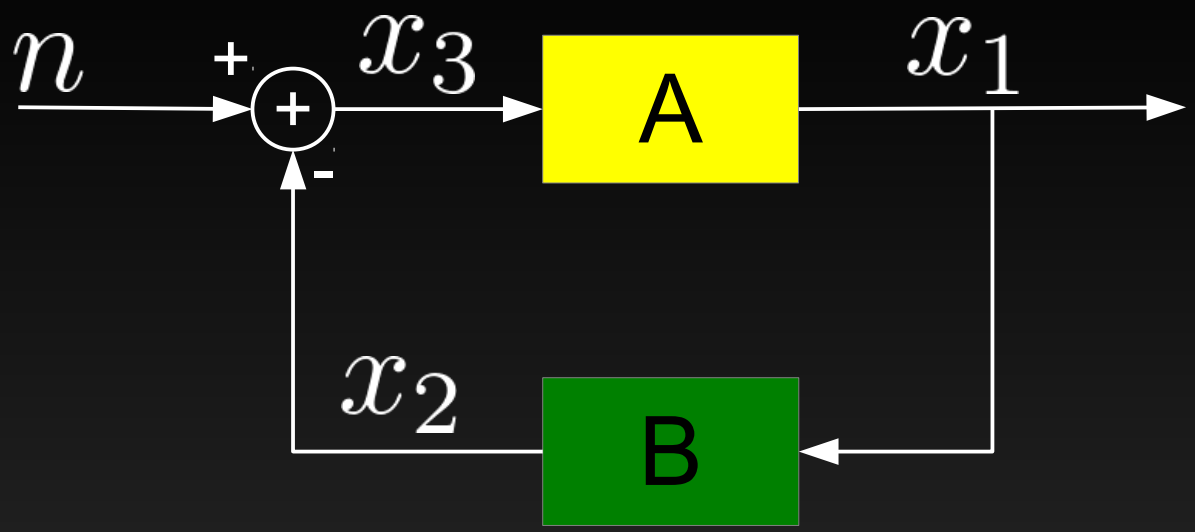

n
+
+
-
x_3
A
x_1
x_2
B



$$x_1 = A(\omega)x_3$$

$$x_2 = B(\omega)x_1$$

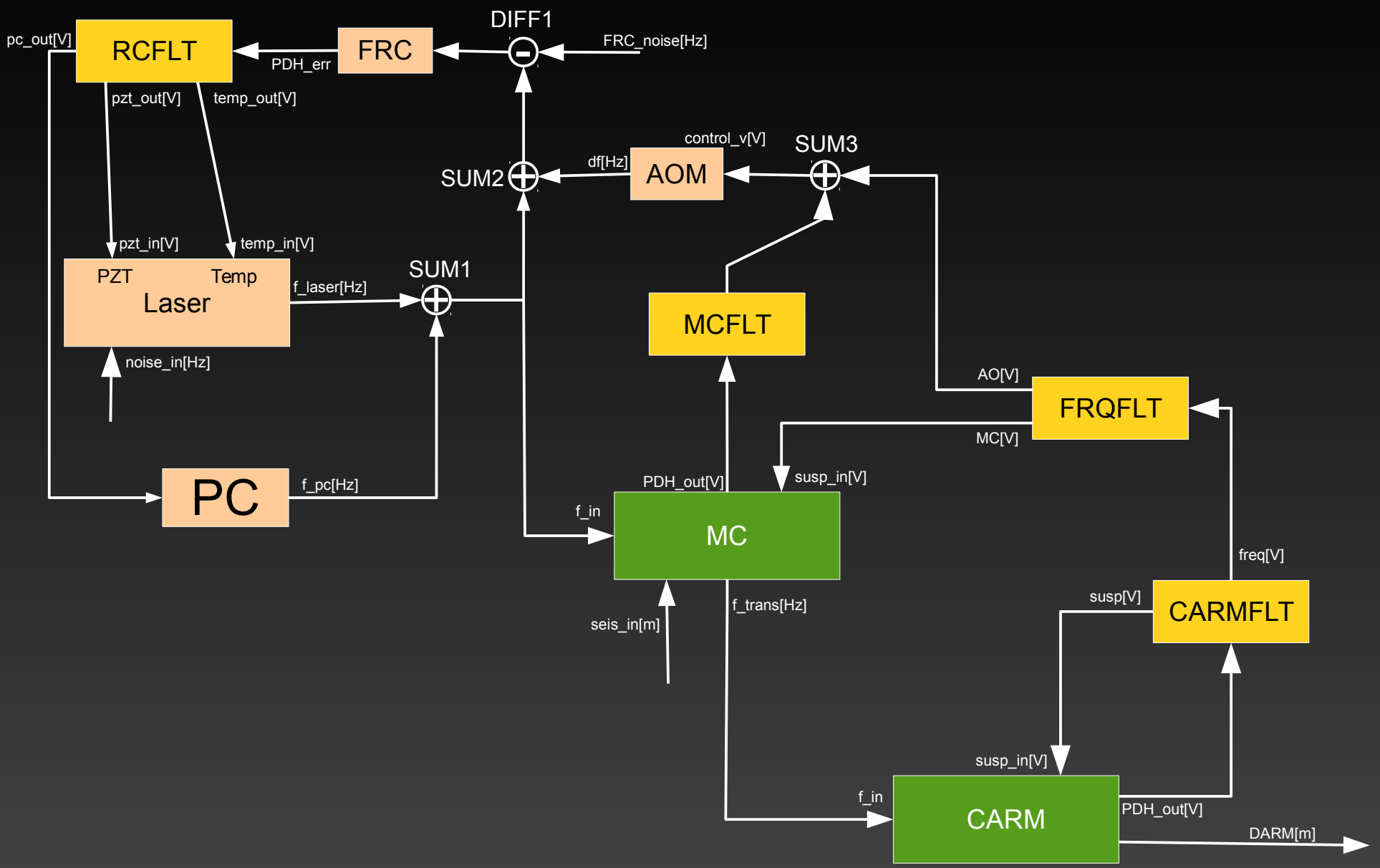
$$x_3 = n - x_2$$

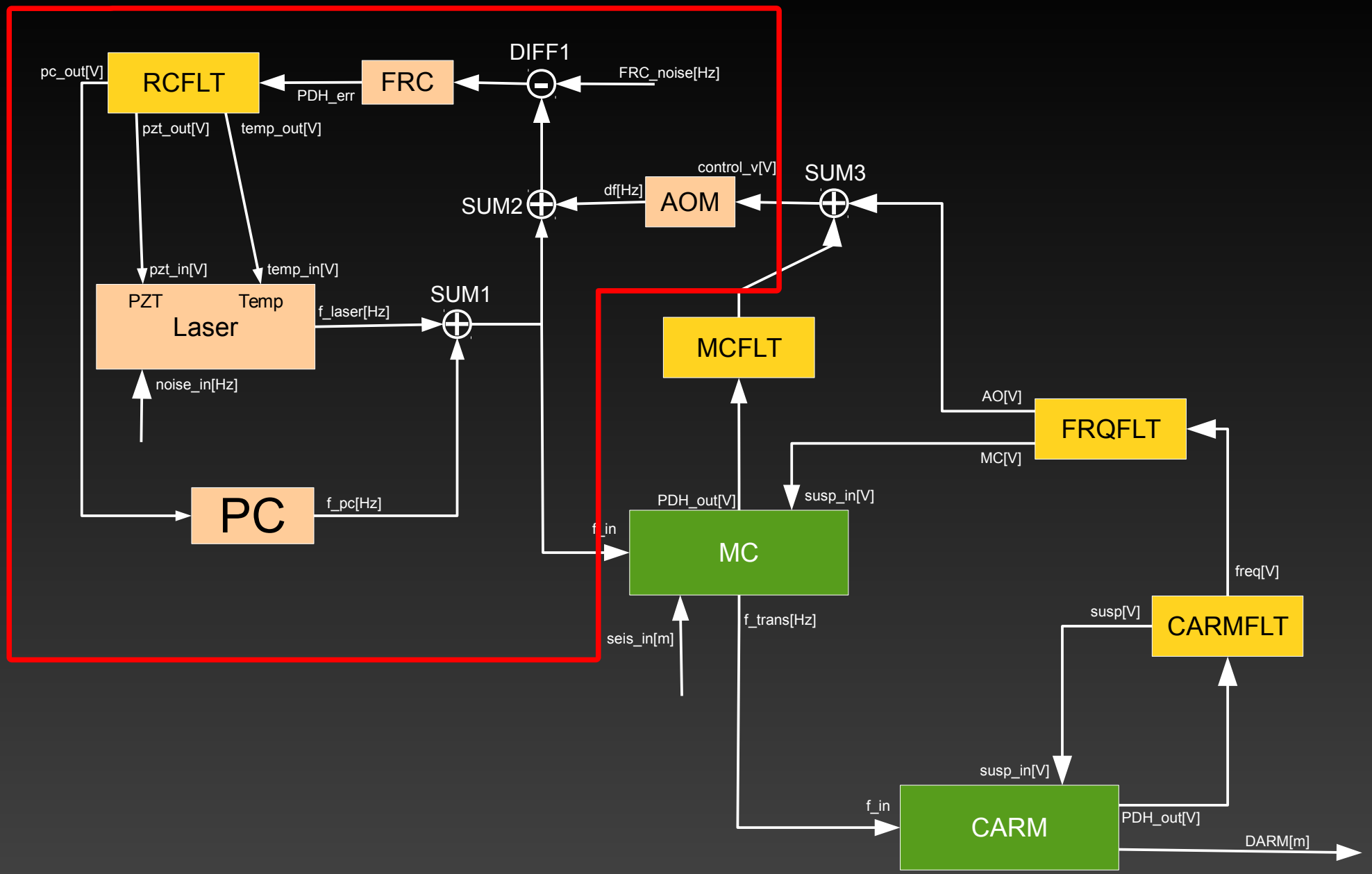


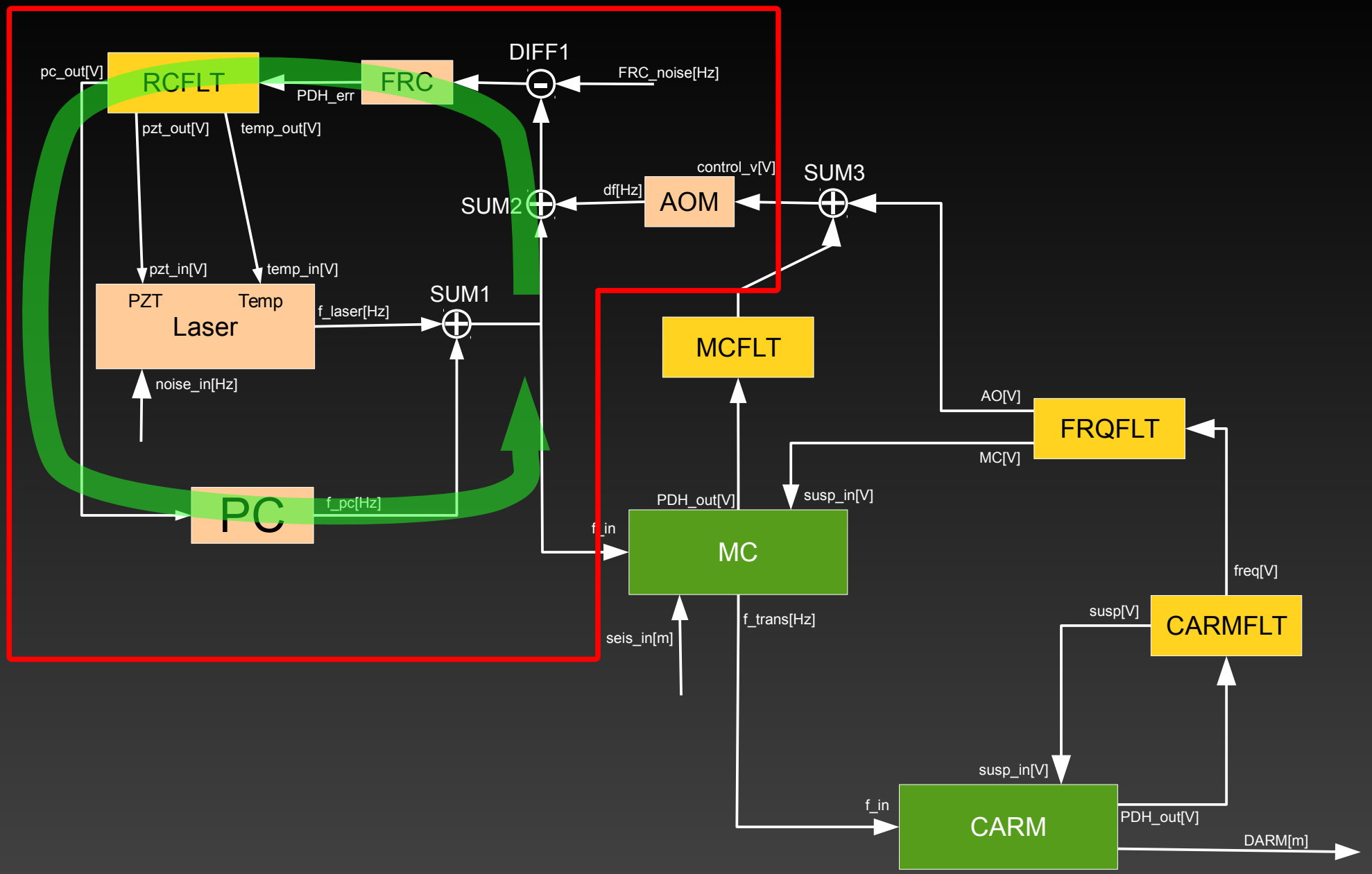
$$\begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} = \begin{pmatrix} 0 & 0 & A(\omega) \\ B(\omega) & 0 & 0 \\ 0 & -1 & 0 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ n \end{pmatrix}$$

$$\vec{x} \qquad M \qquad \vec{x} \qquad \vec{e}$$

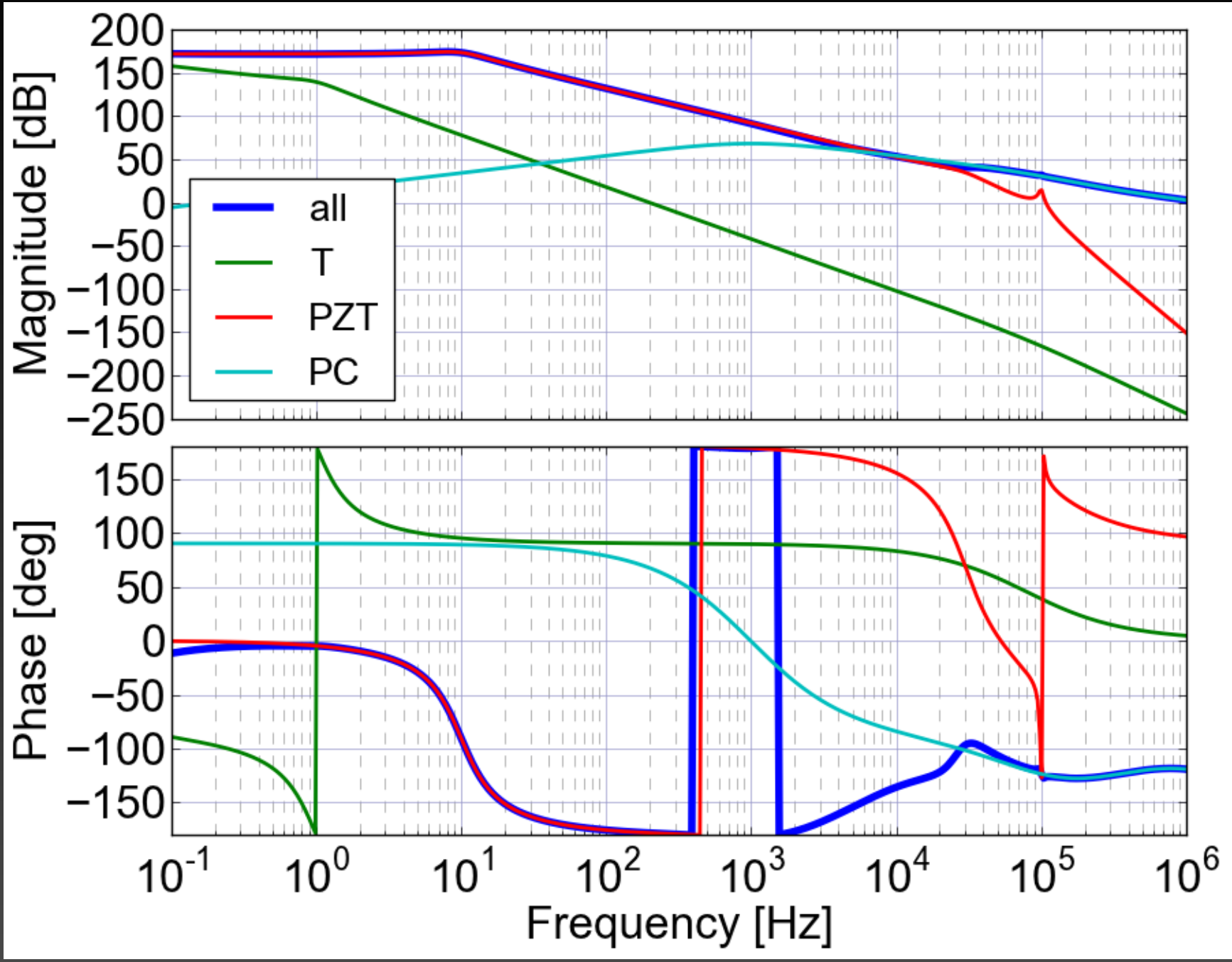
$$\vec{x} = (I - M)^{-1}\vec{e}$$

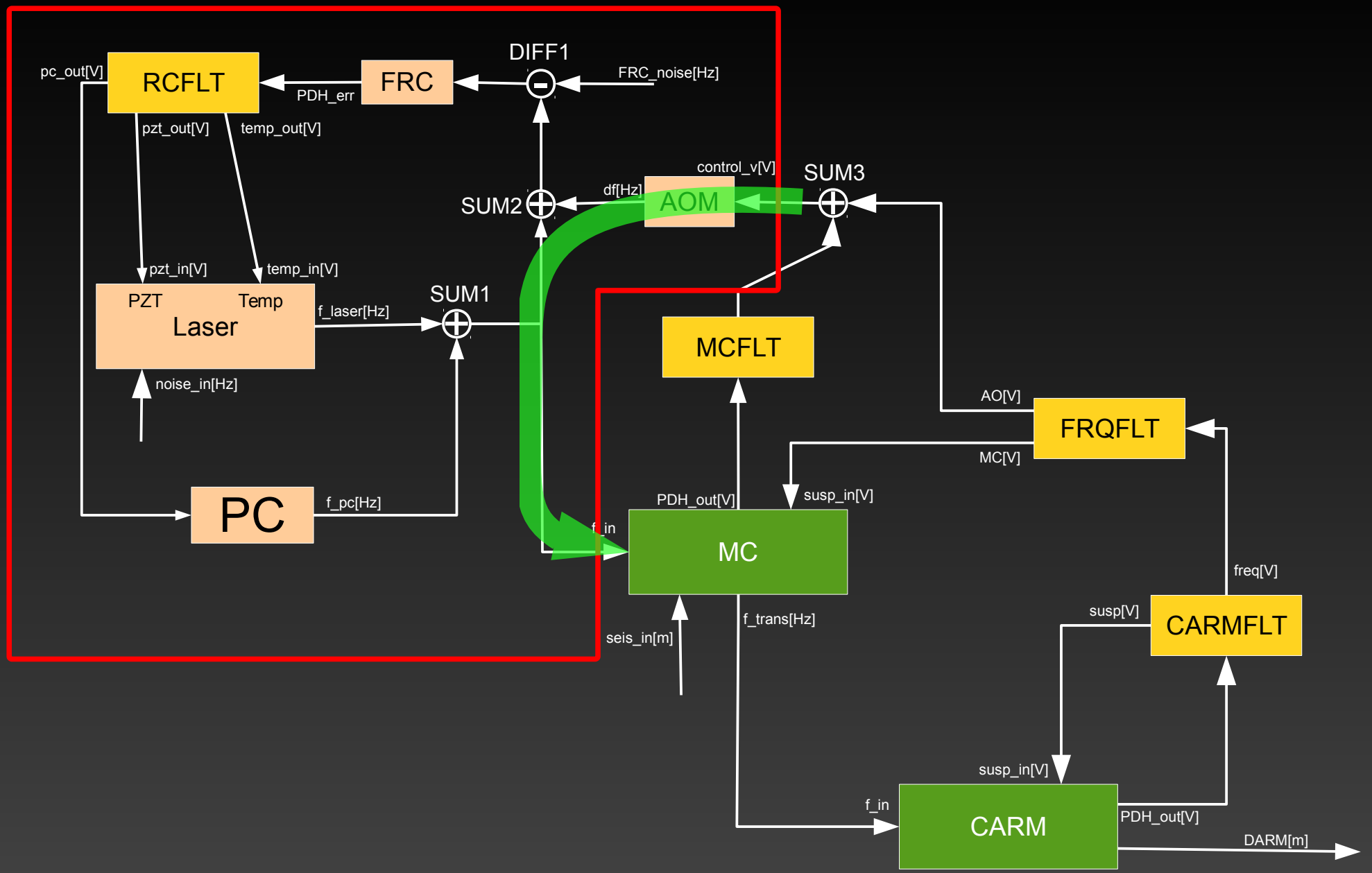

DIFF1
pc_out[V]
RCFLT
FRC
FRC_noise[Hz]
PDH_err
pzt_out[V]
temp_out[V]
control_v[V]
SUM3
df[Hz]
AOM
SUM2
pzt_in[V]
temp_in[V]
PZT
Temp
Laser
f_laser[Hz]
SUM1
MCFLT
noise_in[Hz]
AO[V]
FRQFLT
MC[V]
susp_in[V]
PDH_out[V]
PC
f_pc[Hz]
f_in
MC
freq[V]
susp[V]
CARMFLT
f_trans[Hz]
seis_in[m]
susp_in[V]
f_in
CARM
PDH_out[V]
DARM[m]

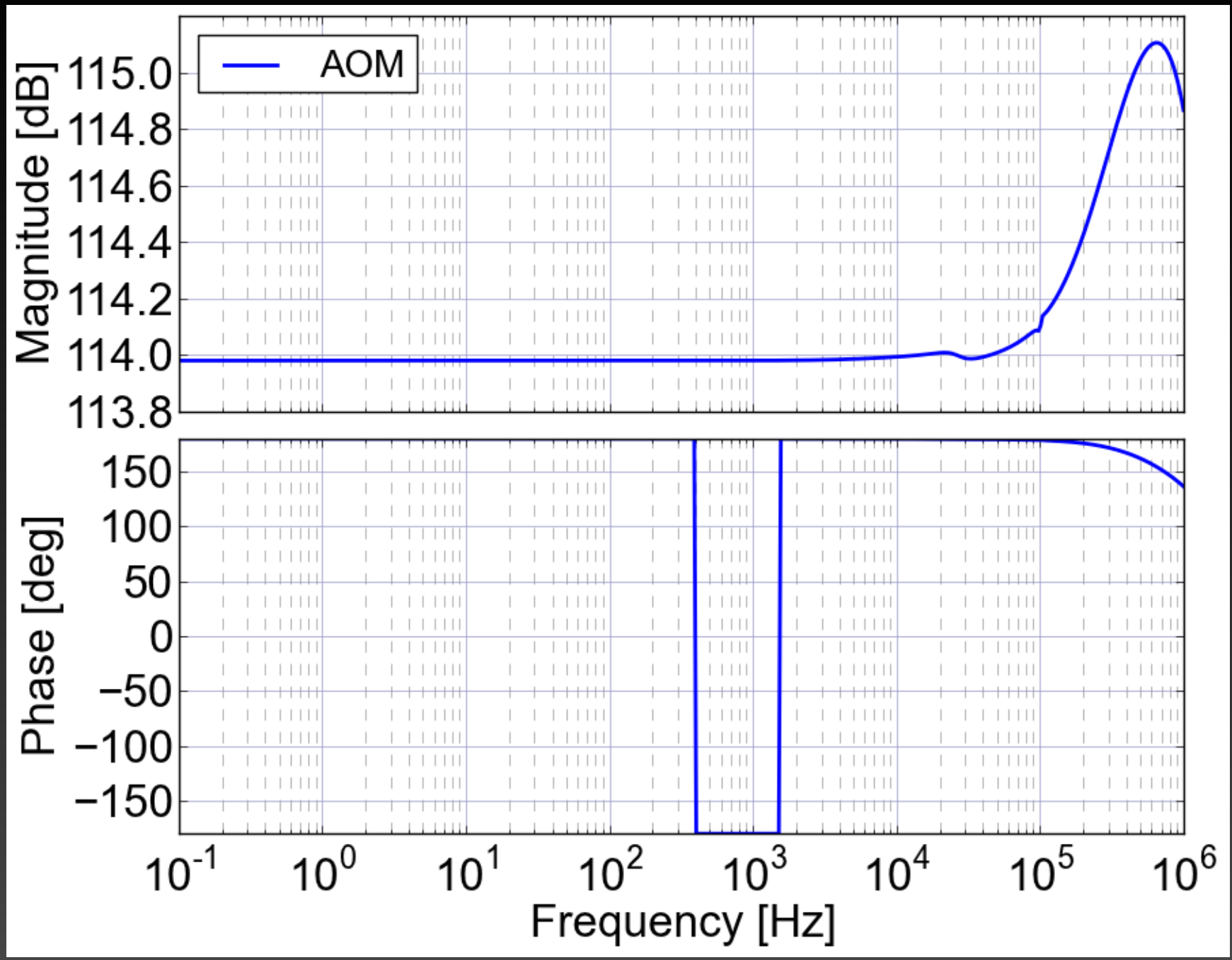

pc_out[V]
RCFLT
PDH_err
FRC
DIFF1
FRC_noise[Hz]
pzt_out[V]
temp_out[V]
control_v[V]
SUM3
df[Hz]
AOM
SUM2
pzt_in[V]
temp_in[V]
PZT
Temp
Laser
f_laser[Hz]
SUM1
MCFLT
noise_in[Hz]
AO[V]
FRQFLT
MC[V]
susp_in[V]
PDH_out[V]
PC
f_pc[Hz]
f_in
MC
freq[V]
susp[V]
CARMFLT
f_trans[Hz]
seis_in[m]
susp_in[V]
f_in
CARM
PDH_out[V]
DARM[m]

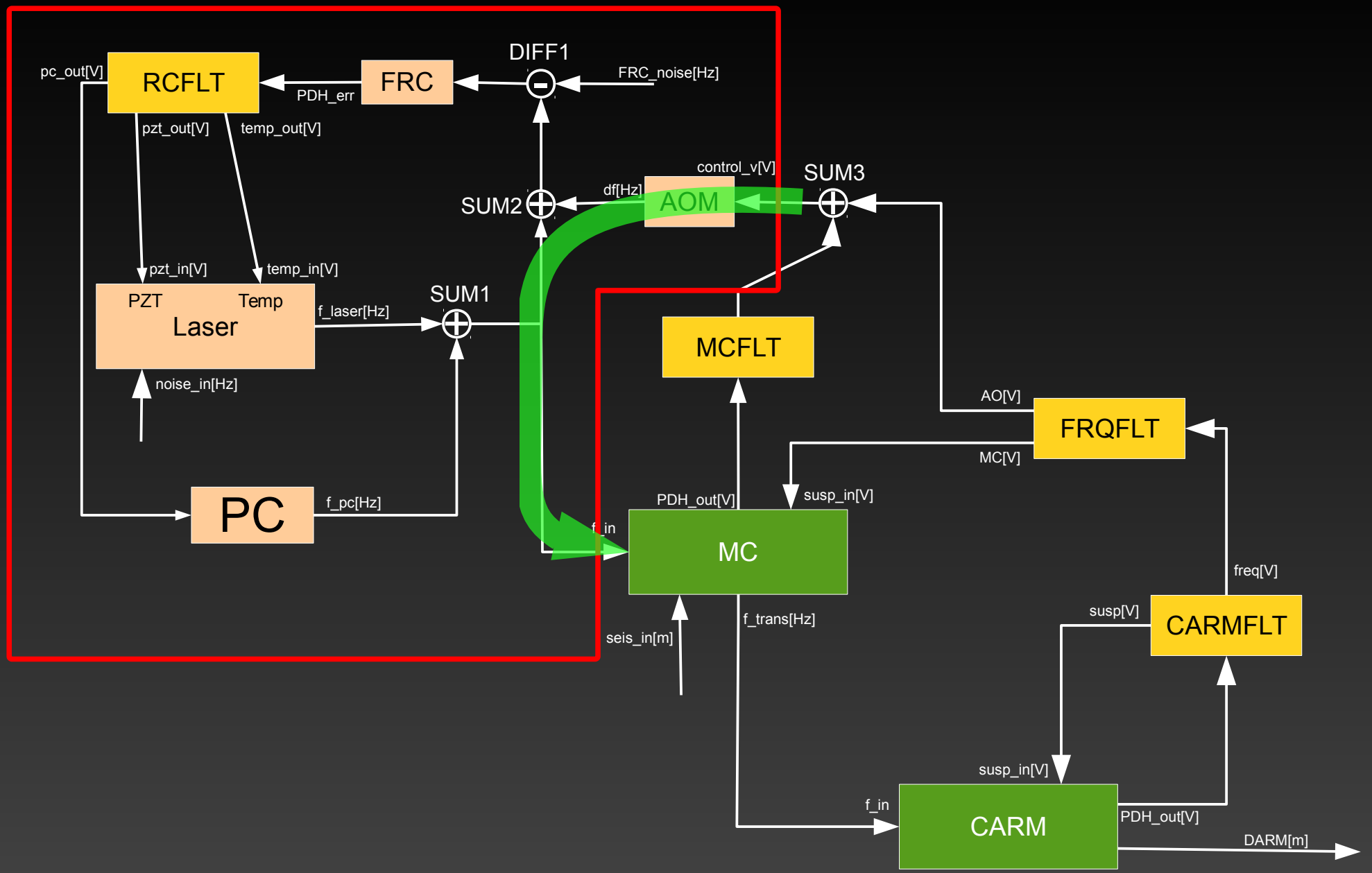

pc_out[V]
RCFLT
FRC
PDH_err
DIFF1
FRC_noise[Hz]
pzt_out[V]
temp_out[V]
control_v[V]
SUM3
df[Hz]
AOM
SUM2
pzt_in[V]
temp_in[V]
PZT
Temp
Laser
f_laser[Hz]
SUM1
MCFLT
noise_in[Hz]
AO[V]
FRQFLT
MC[V]
susp_in[V]
PDH_out[V]
PC
f_pc[Hz]
f_in
MC
freq[V]
susp[V]
CARMFLT
f_trans[Hz]
seis_in[m]
susp_in[V]
f_in
CARM
PDH_out[V]
DARM[m]

Reference Cavity Open Loop Gain

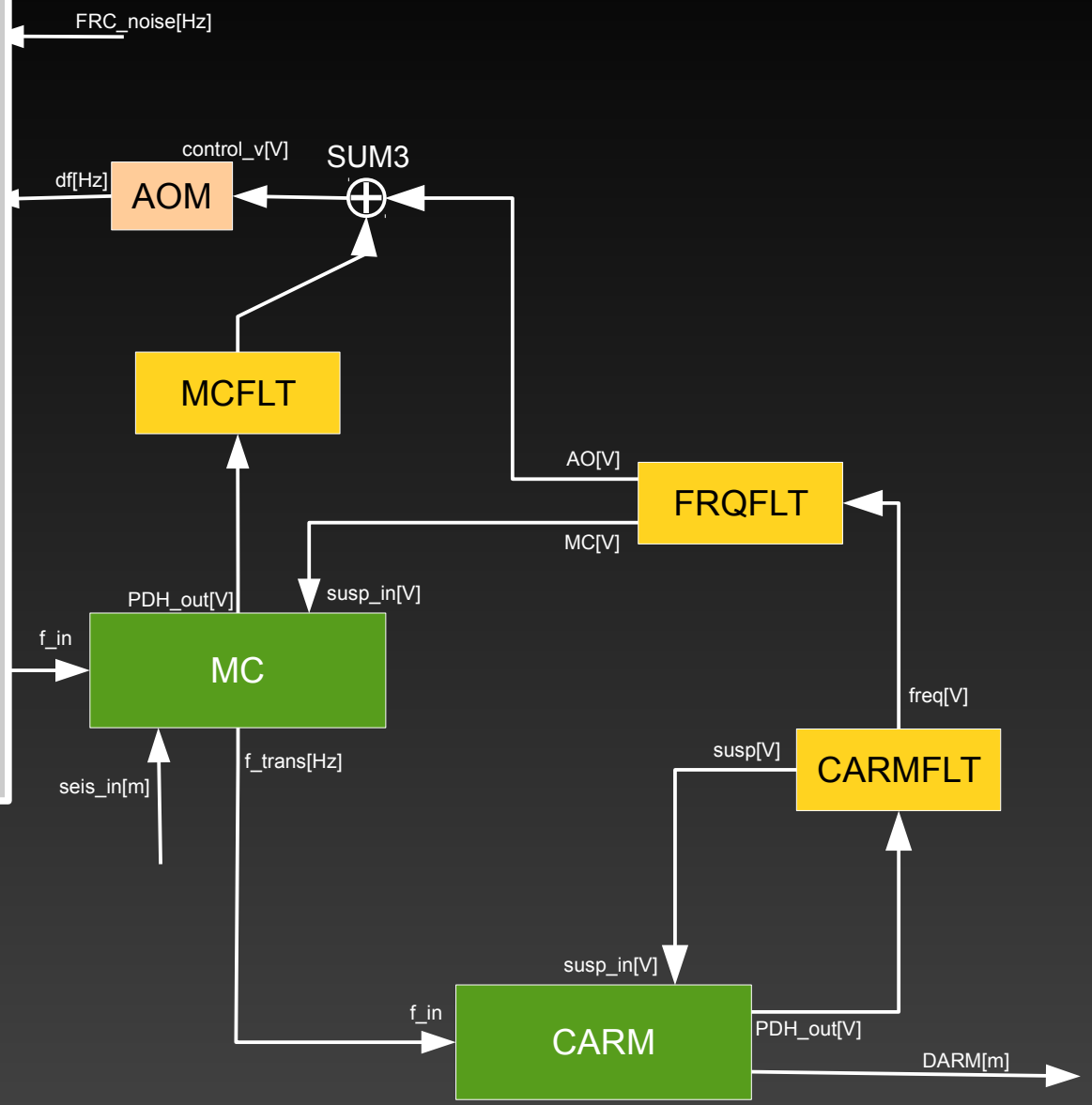



pc_out[V]
RCFLT
PDH_err
FRC
DIFF1
FRC_noise[Hz]
pzt_out[V]
temp_out[V]
control_v[V]
SUM3
df[Hz]
SUM2
AOM
pzt_in[V]
temp_in[V]
PZT
Temp
Laser
f_laser[Hz]
SUM1
MCFLT
noise_in[Hz]
AO[V]
FRQFLT
MC[V]
PC
f_pc[Hz]
PDH_out[V]
susp_in[V]
f_in
MC
freq[V]
susp[V]
CARMFLT
seis_in[m]
f_trans[Hz]
susp_in[V]
f_in
CARM
PDH_out[V]
DARM[m]

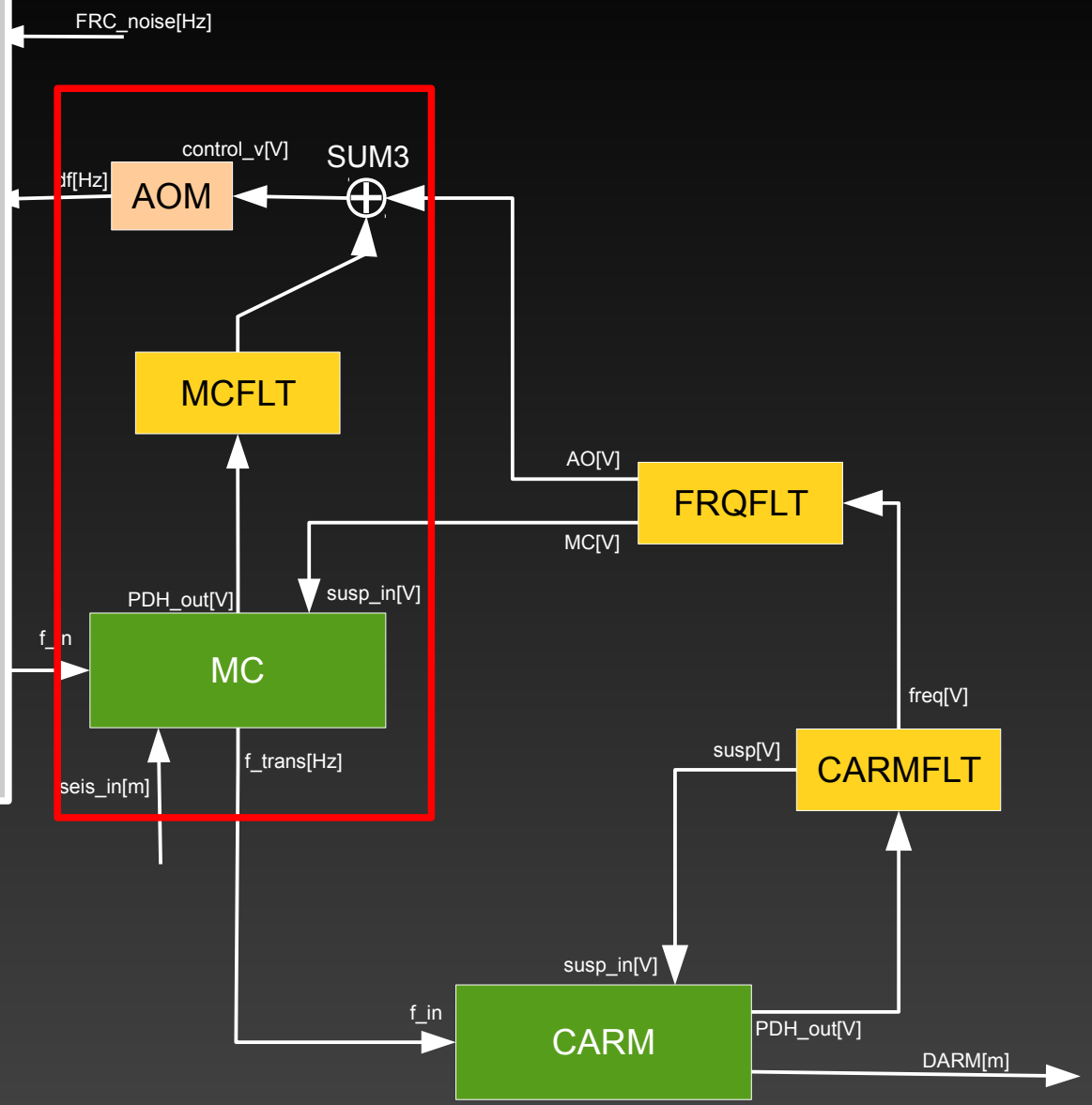

AOM
Magnitude [dB]
115.0
114.8
114.6
114.4
114.2
114.0
113.8
Phase [deg]
150
100
50
0
−50
−100
−150
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
Frequency [Hz]


pc_out[V]
RCFLT
PDH_err
FRC
DIFF1
FRC_noise[Hz]
pzt_out[V]
temp_out[V]
control_v[V]
SUM3
df[Hz]
SUM2
AOM
pzt_in[V]
temp_in[V]
PZT
Temp
Laser
f_laser[Hz]
SUM1
MCFLT
noise_in[Hz]
AO[V]
FRQFLT
MC[V]
PC
f_pc[Hz]
PDH_out[V]
susp_in[V]
f_in
MC
freq[V]
susp[V]
CARMFLT
seis_in[m]
f_trans[Hz]
susp_in[V]
f_in
CARM
PDH_out[V]
DARM[m]

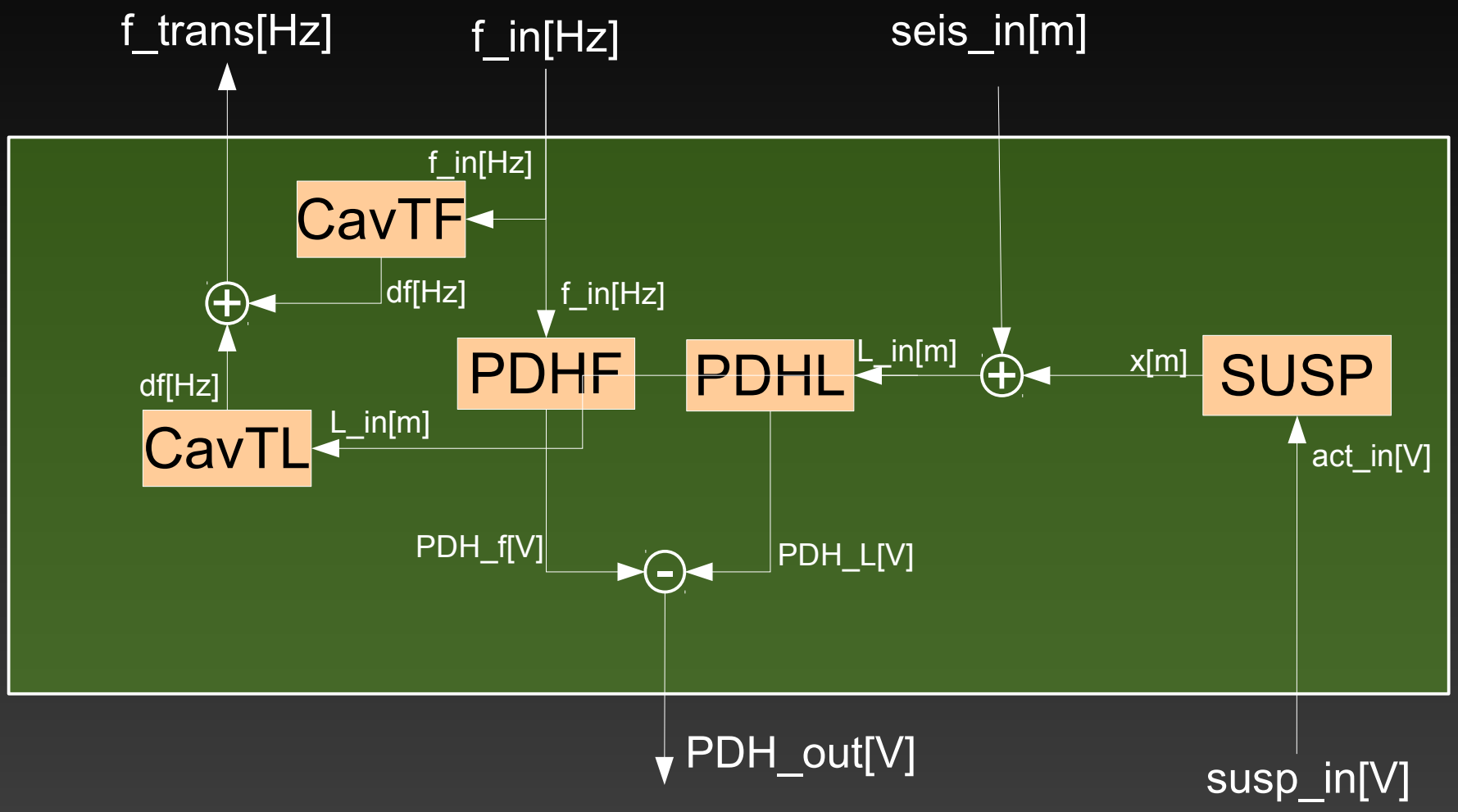
Flat Response <100kHz



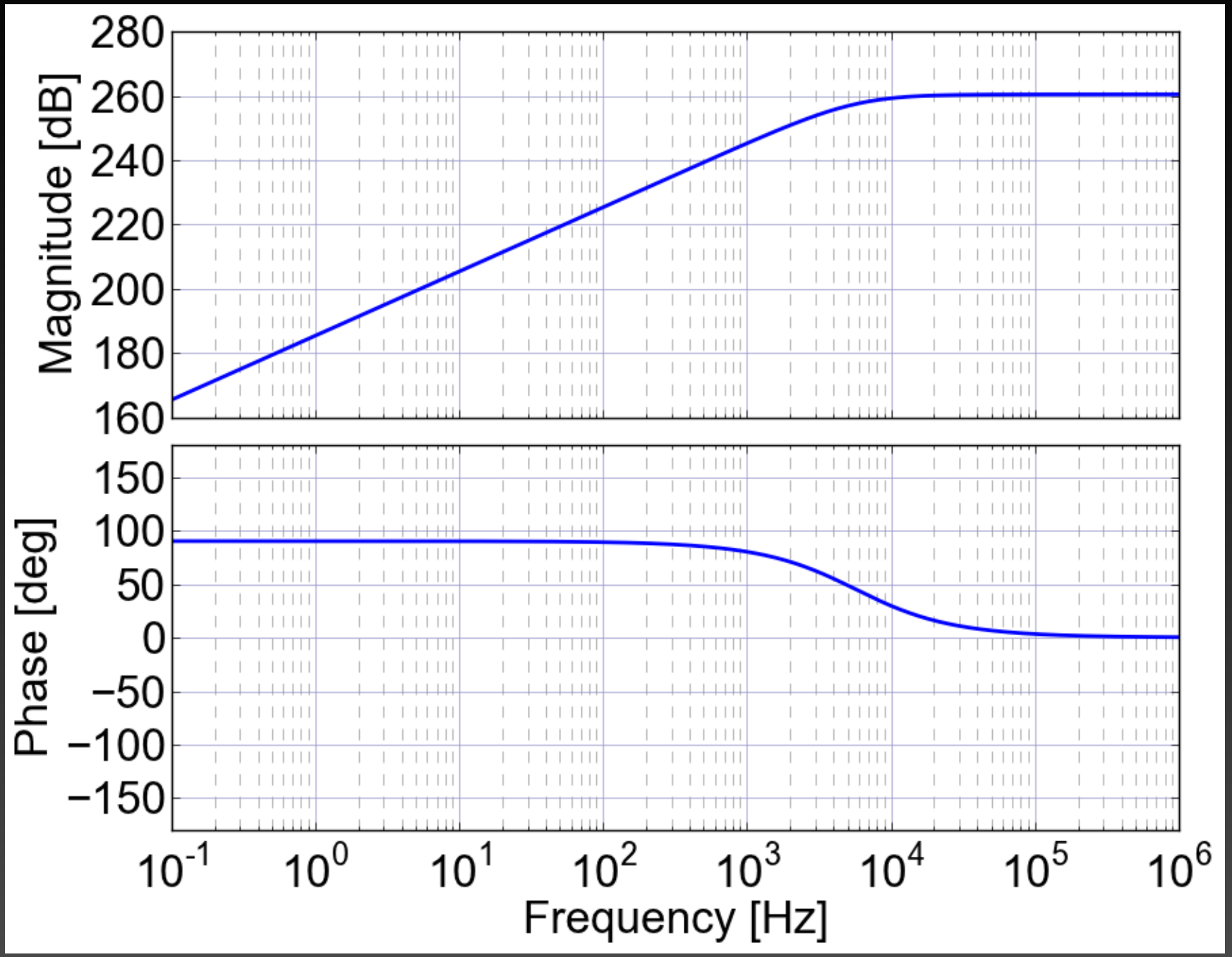
Flat Response <100kHz



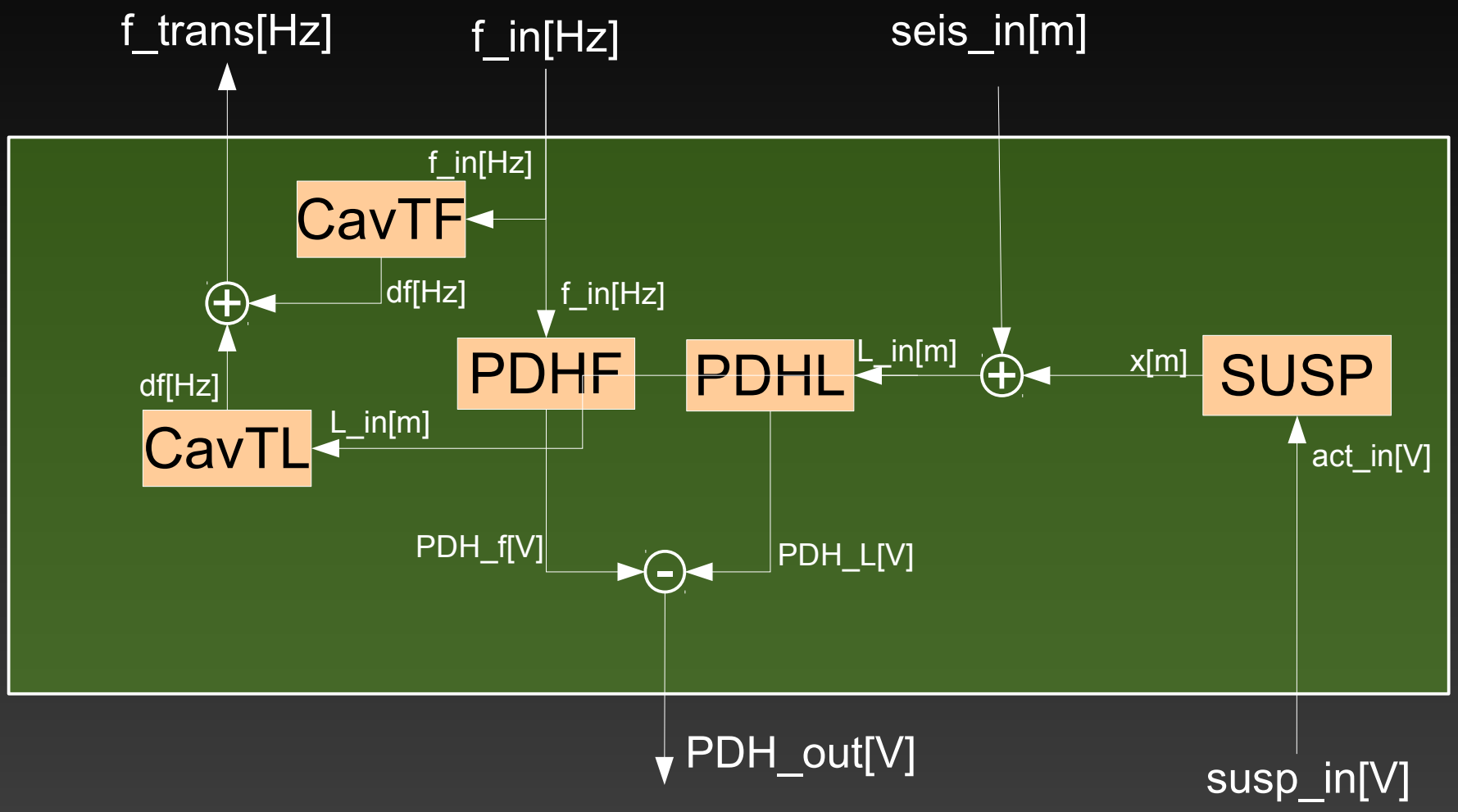
Mode Cleaner



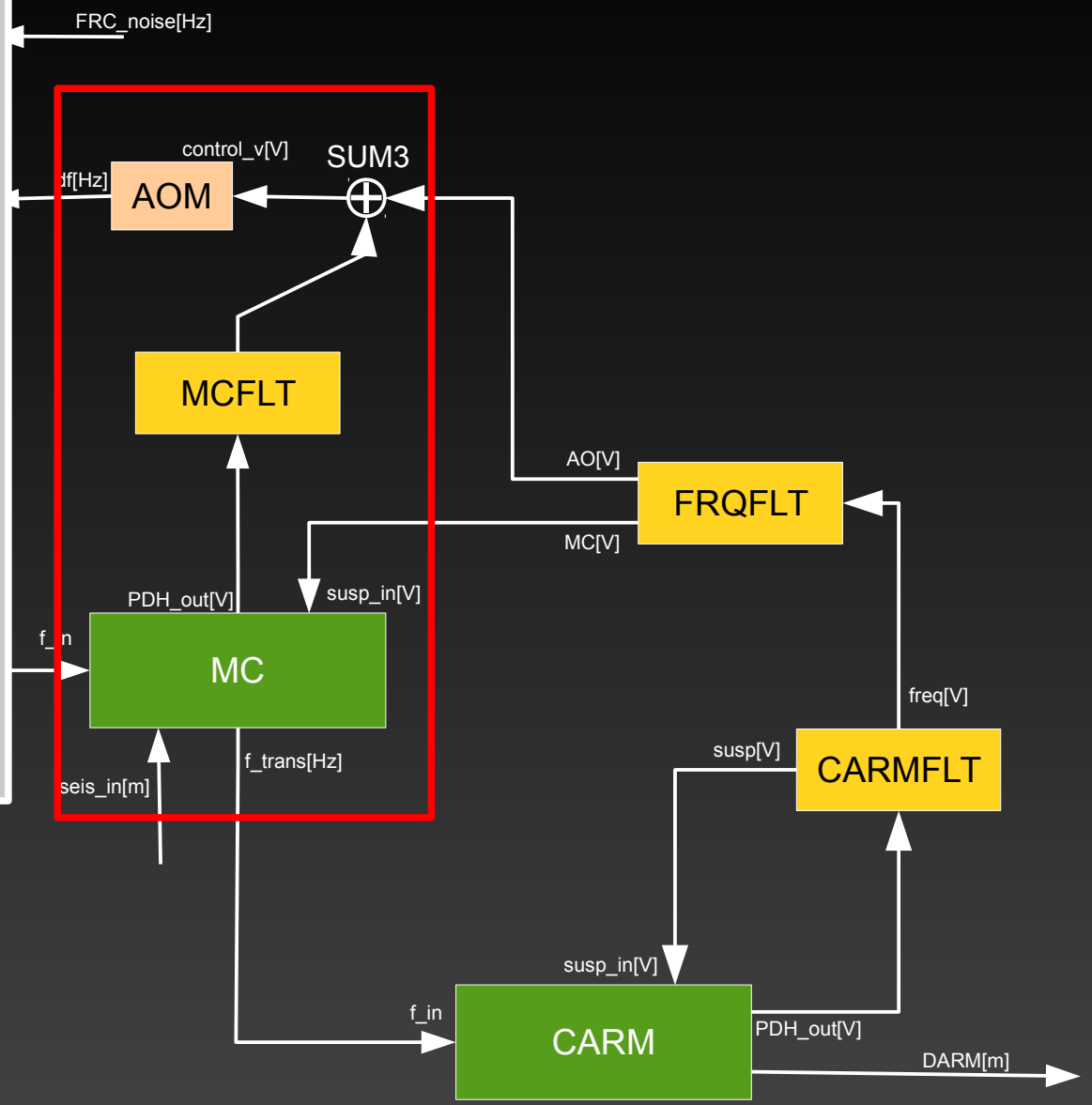
CavTL


Magnitude [dB]
280
260
240
220
200
180
160
Phase [deg]
150
100
50
0
−50
−100
−150
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
Frequency [Hz]

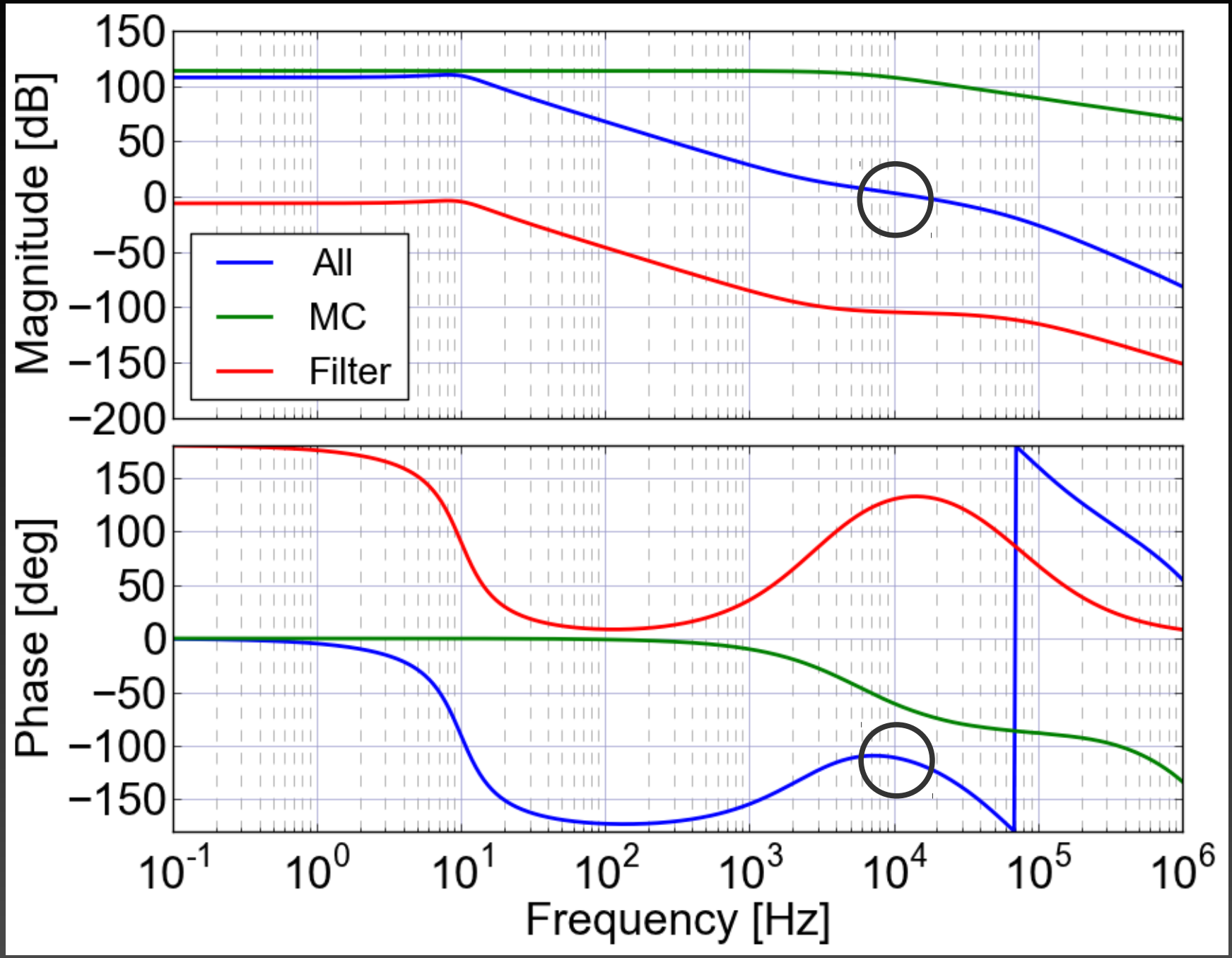
Mode Cleaner



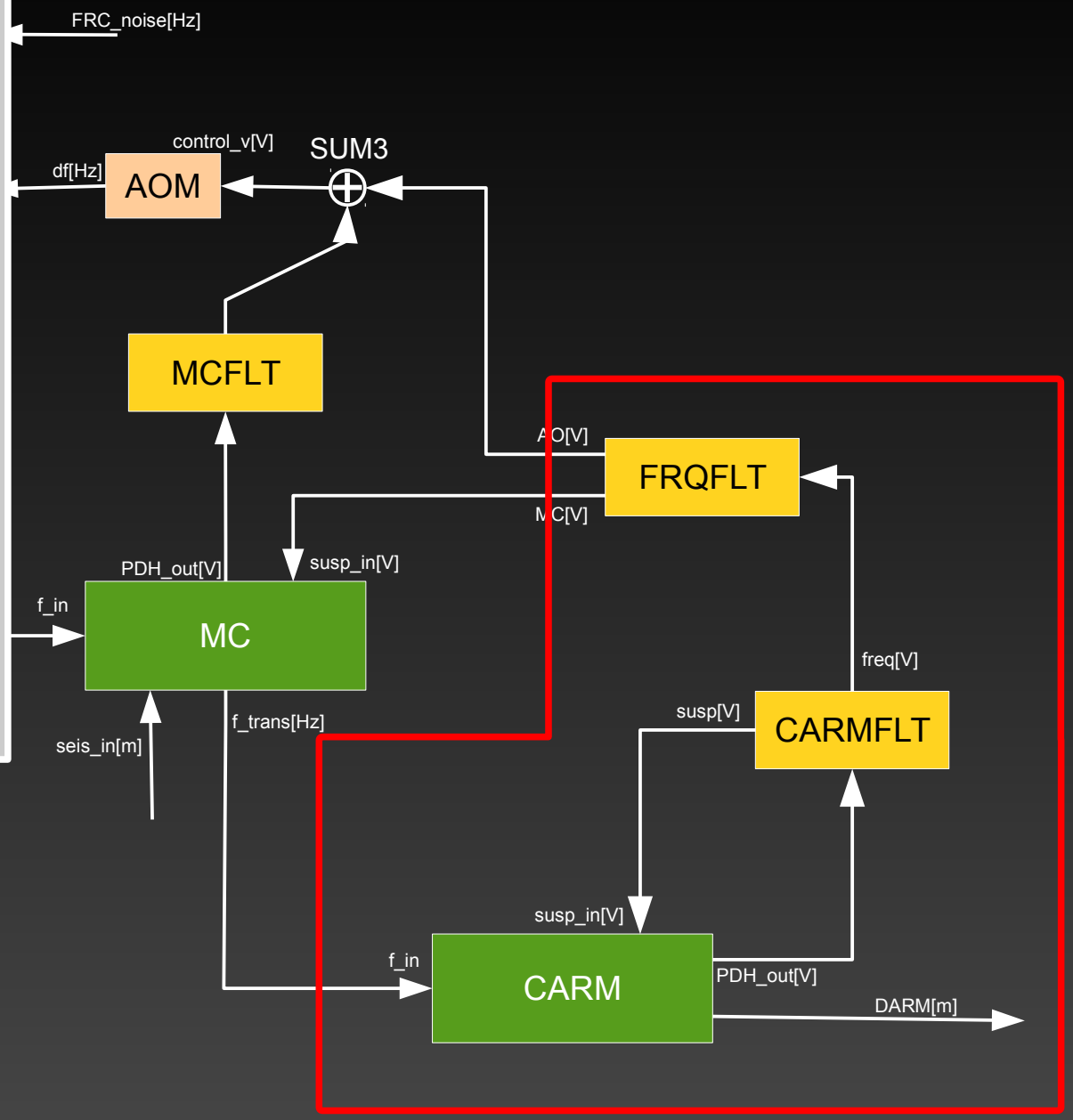
Flat Response <100kHz



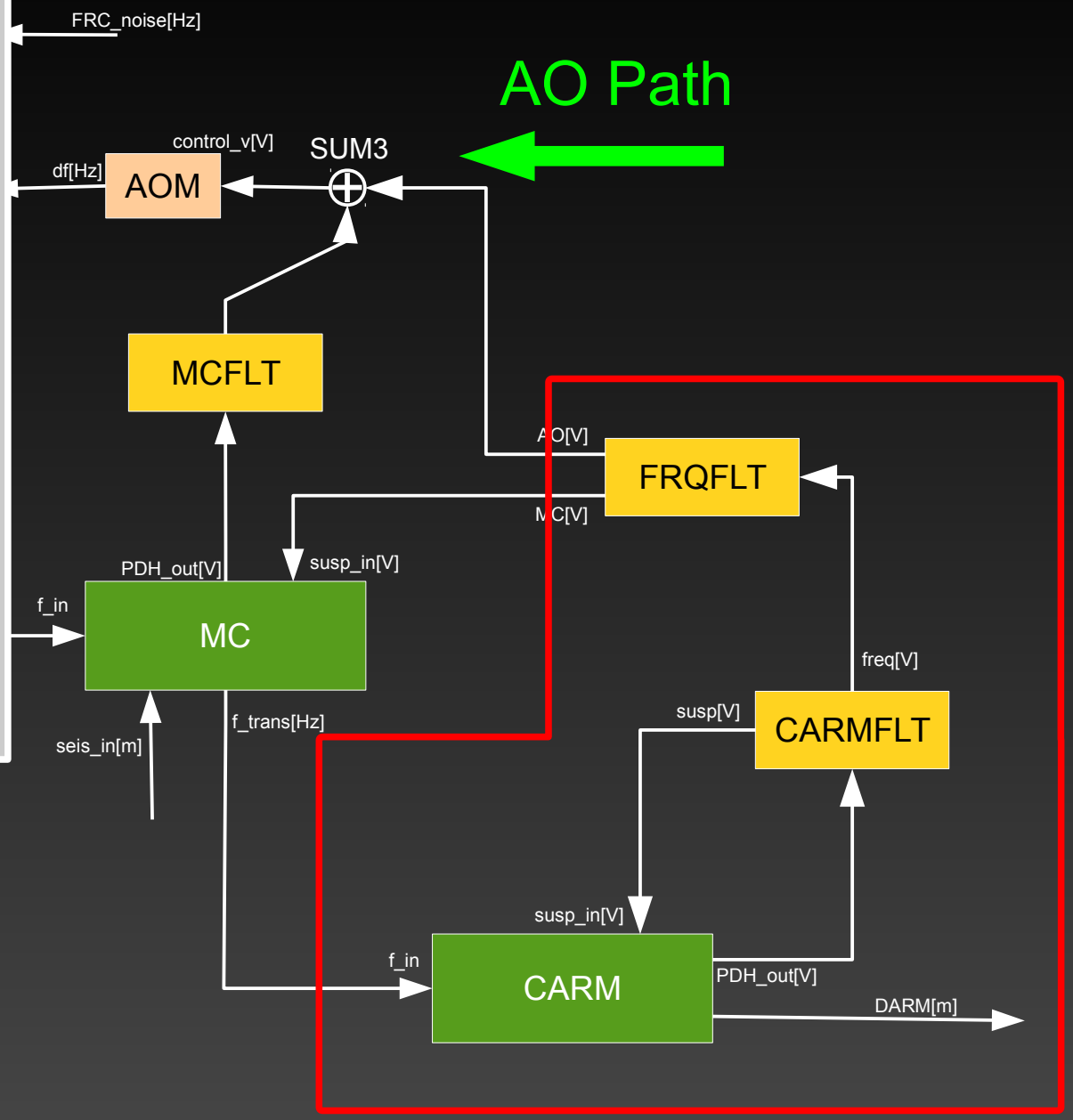
MC Open Loop Gain



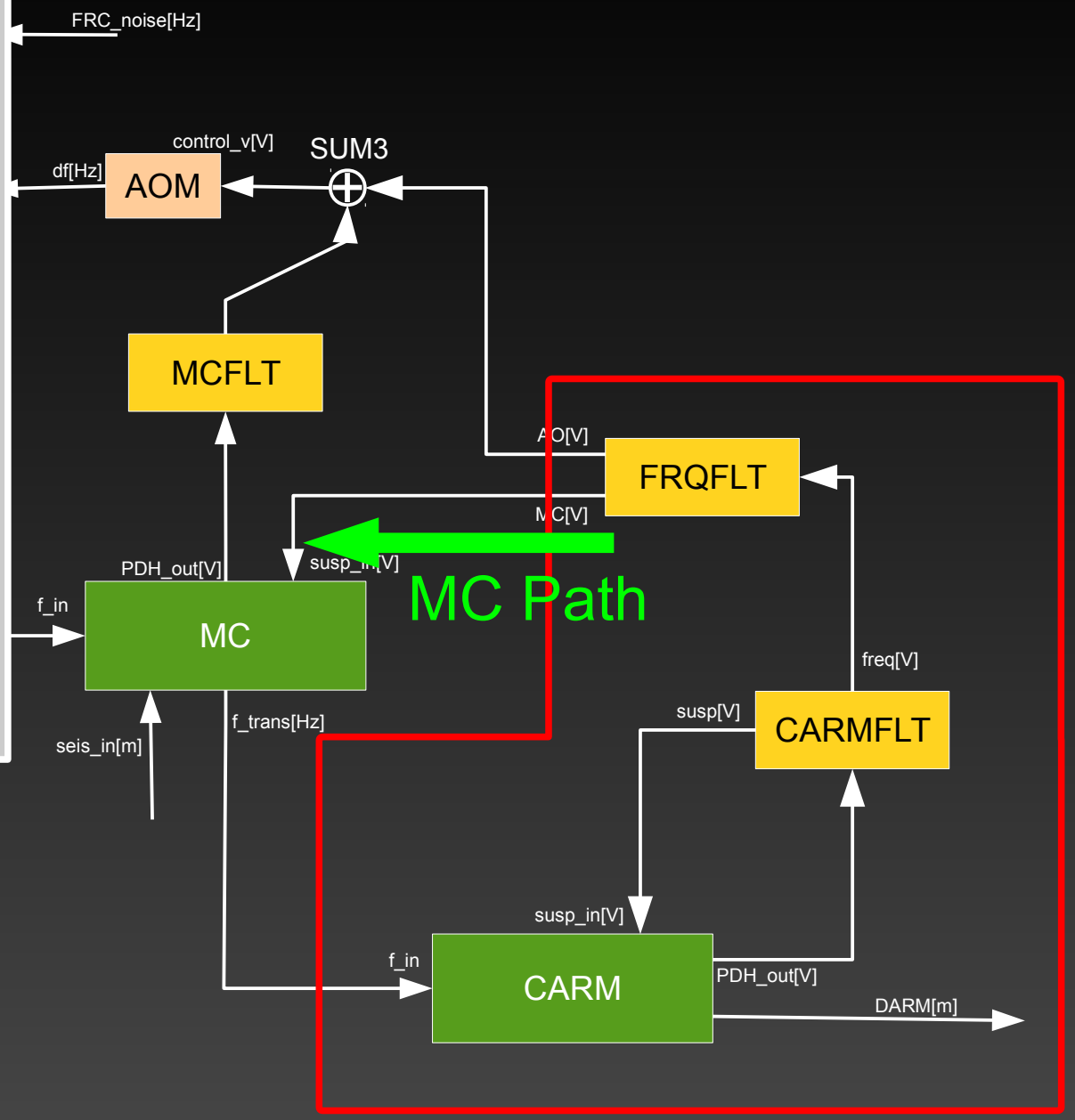
Flat Response <100kHz



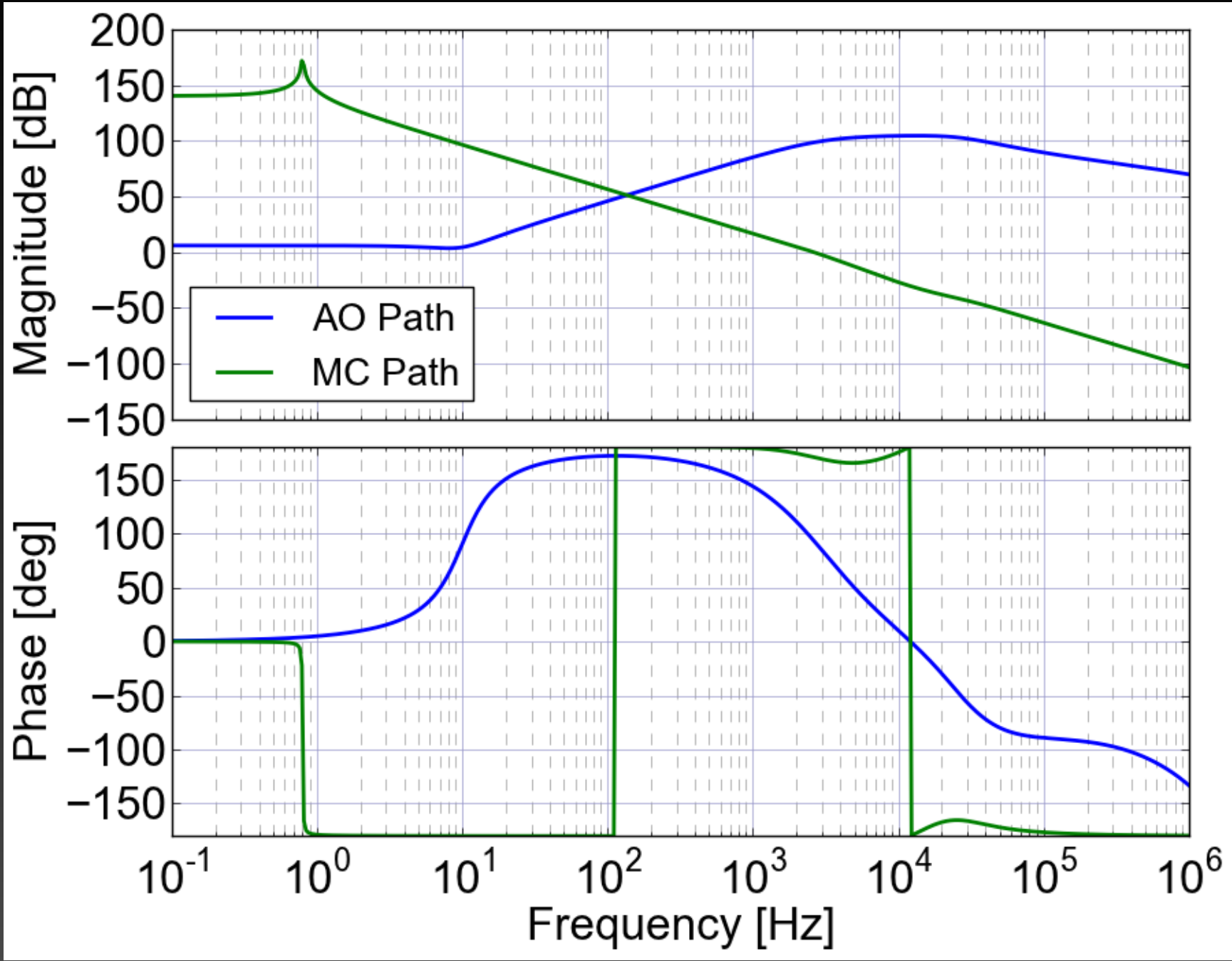
Flat Response <100kHz



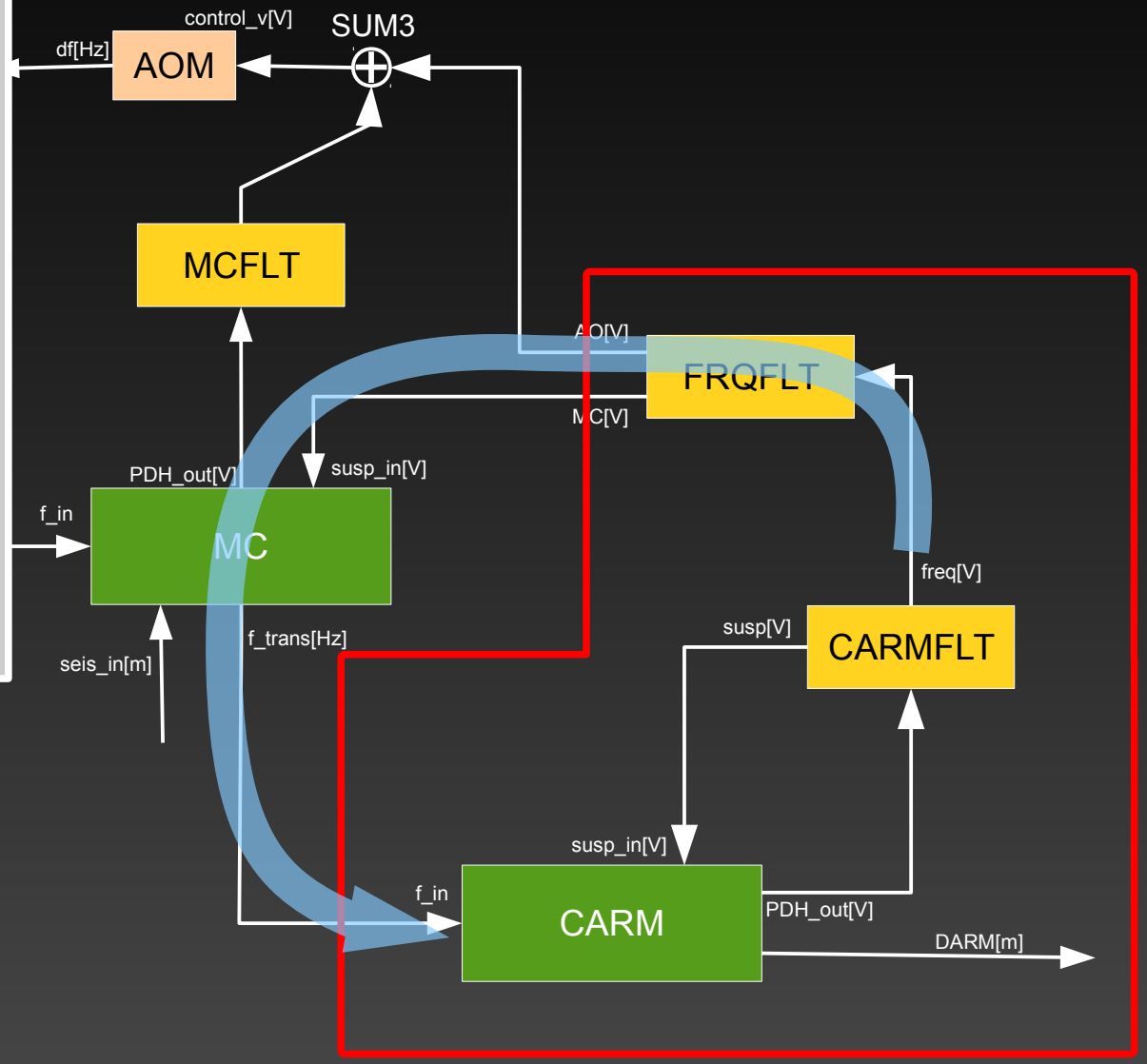
Flat Response <100kHz



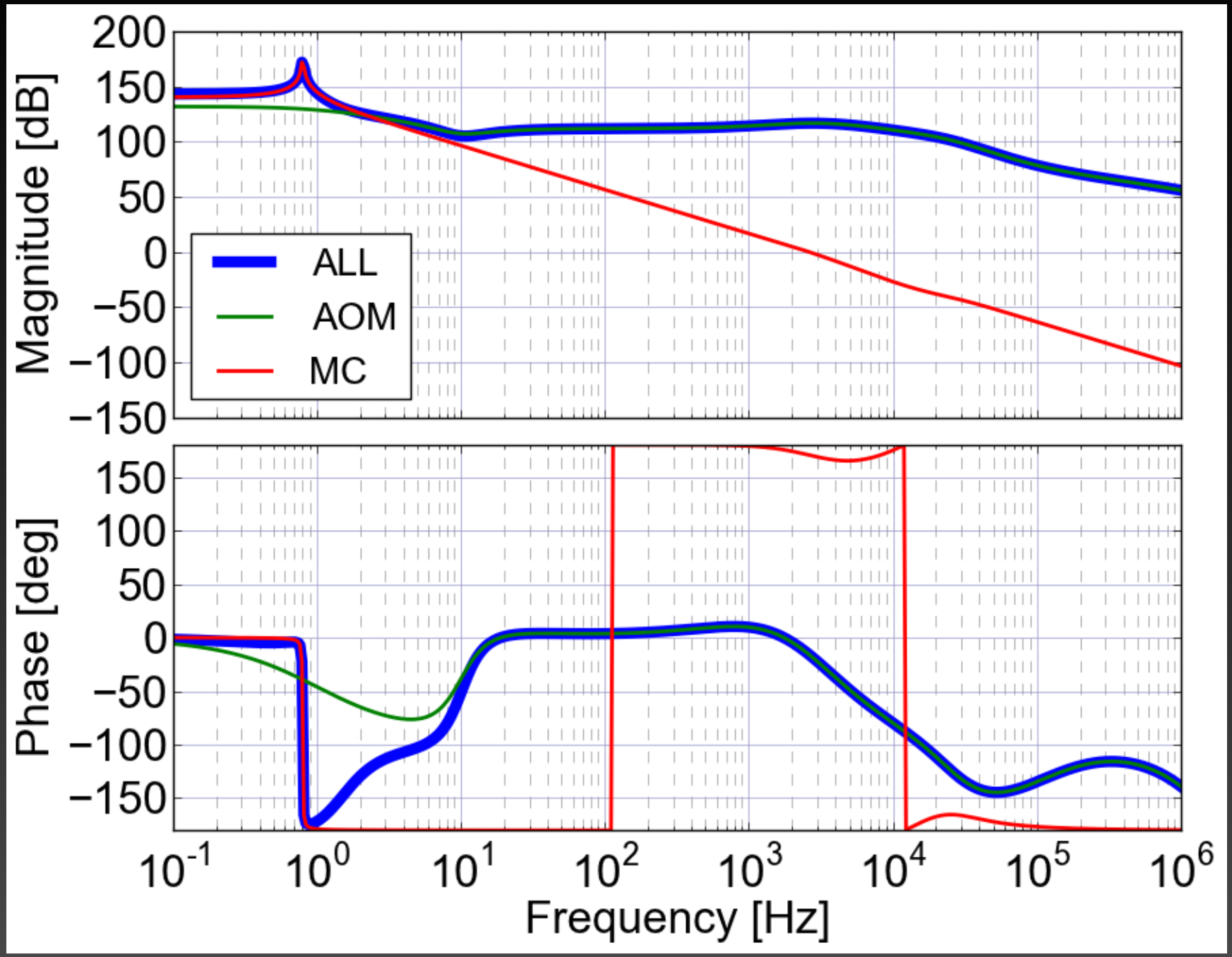
Response of the MC transmission frequency



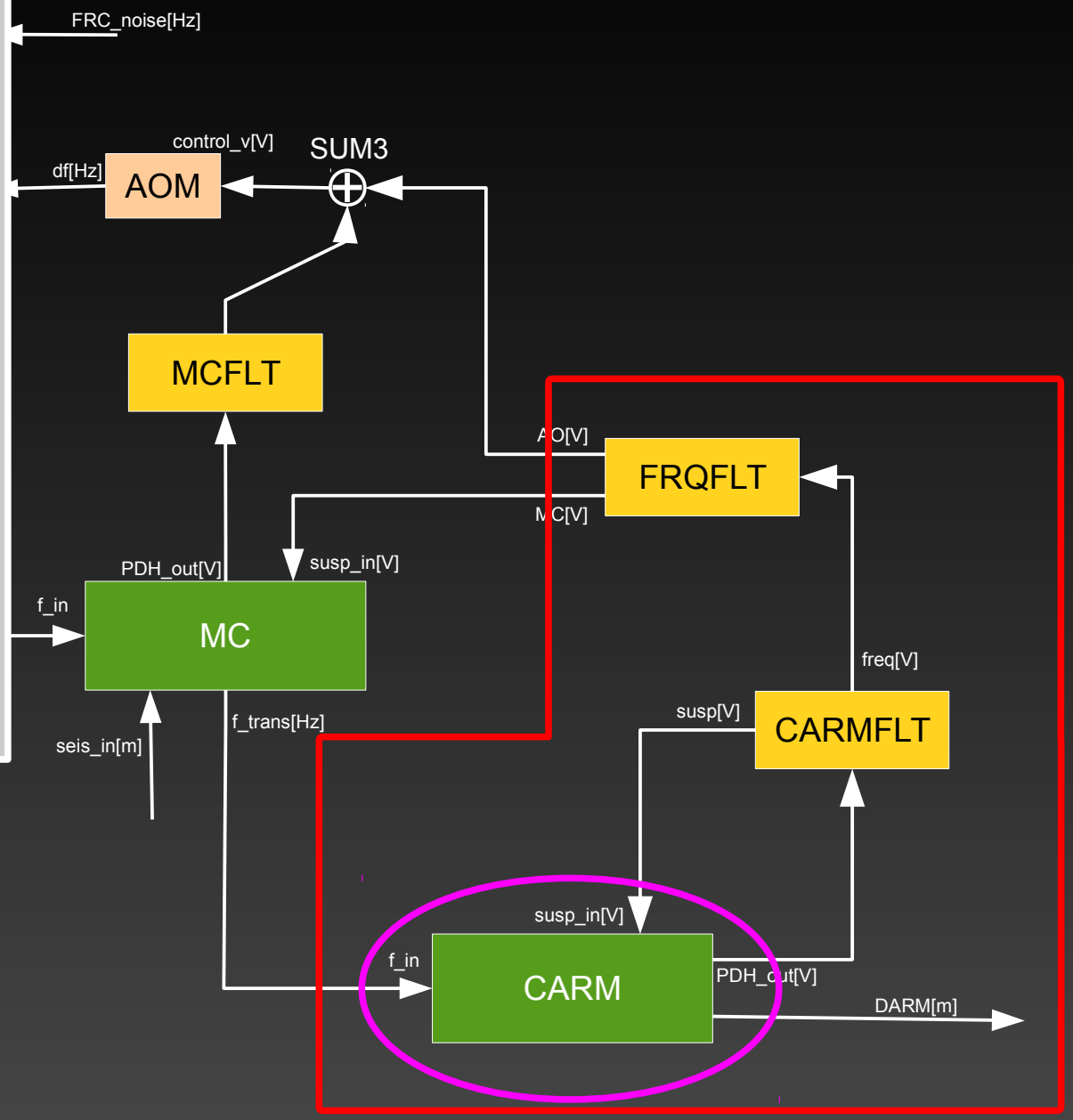
Flat Response <100kHz

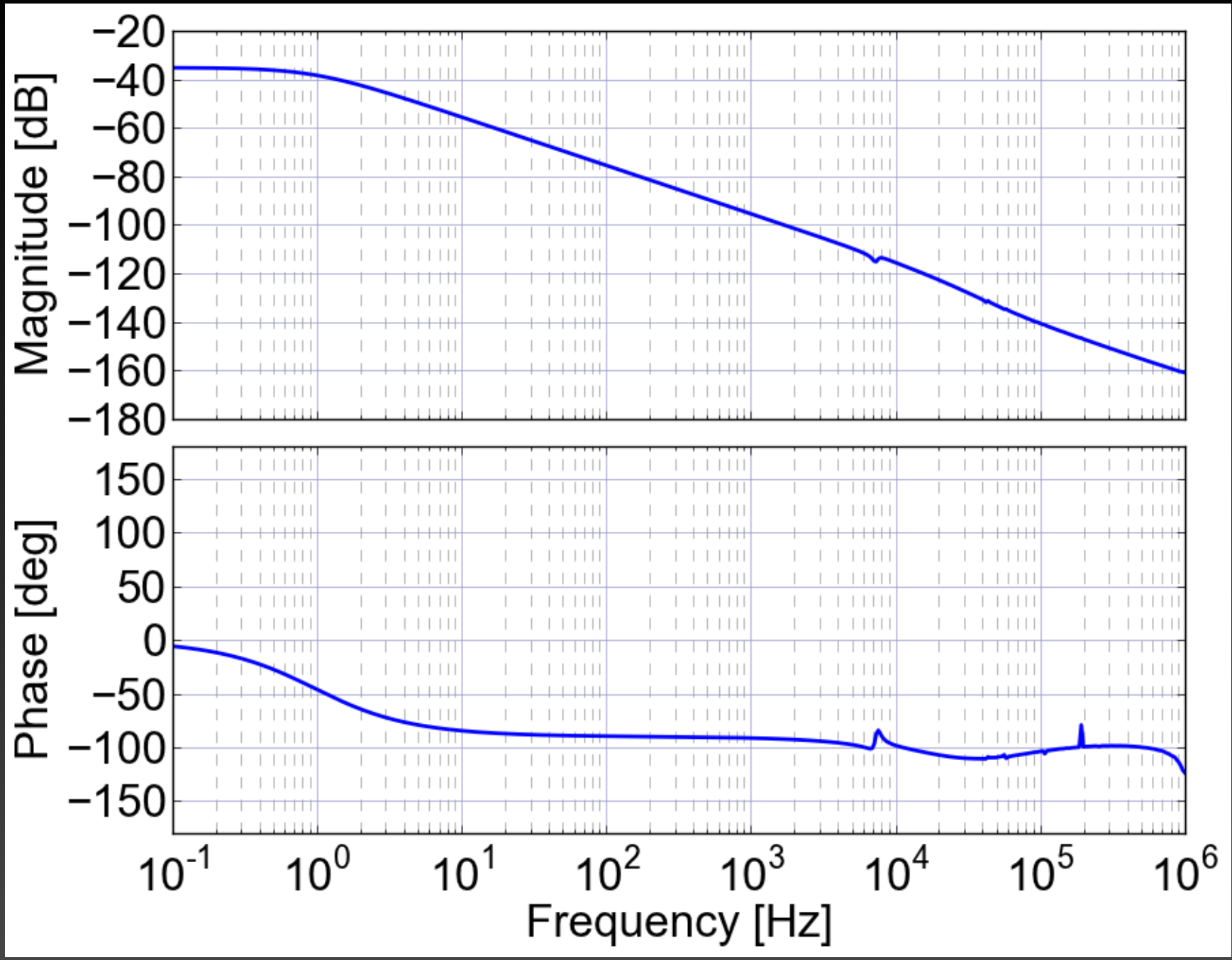


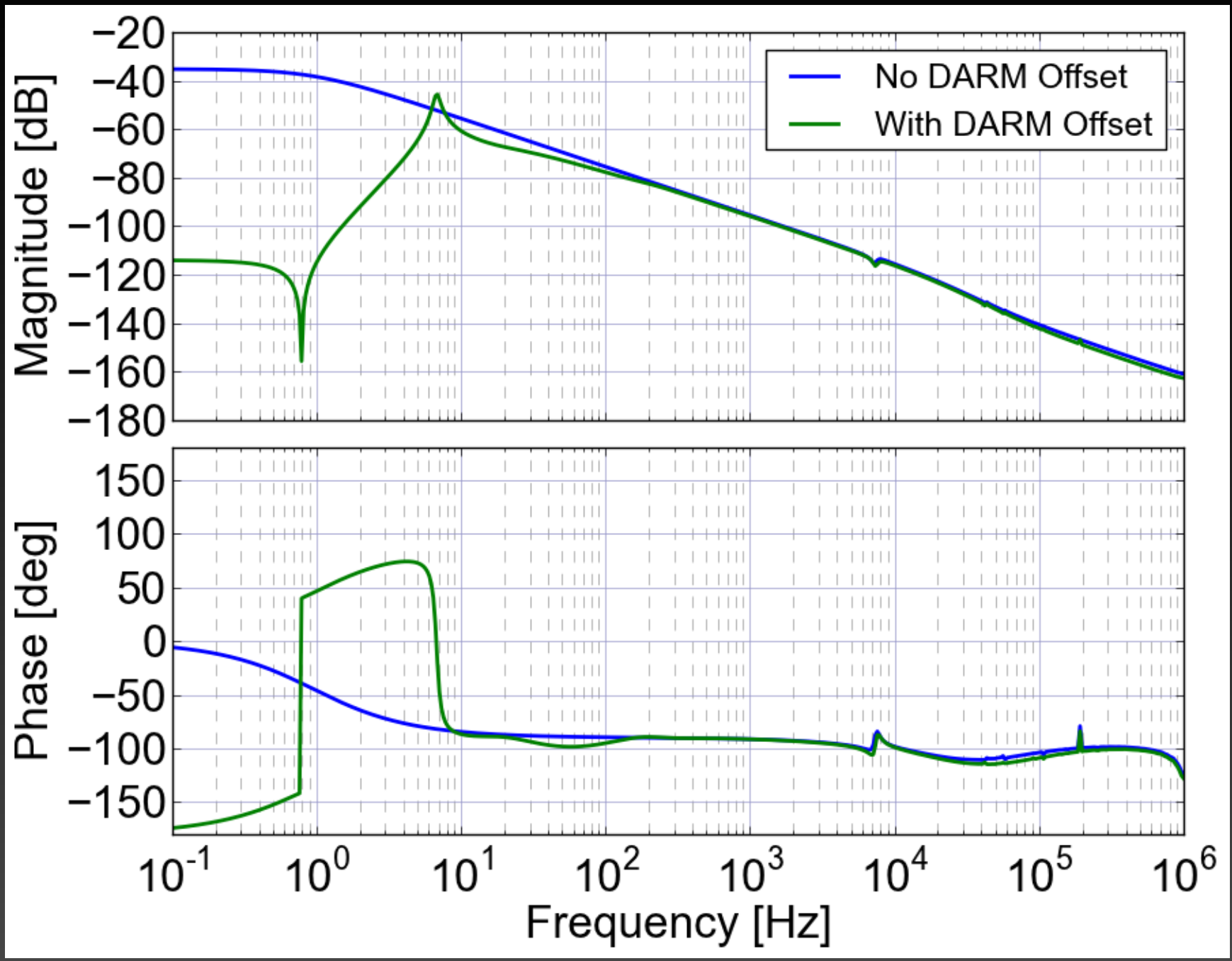
Combined Frequency Actuator

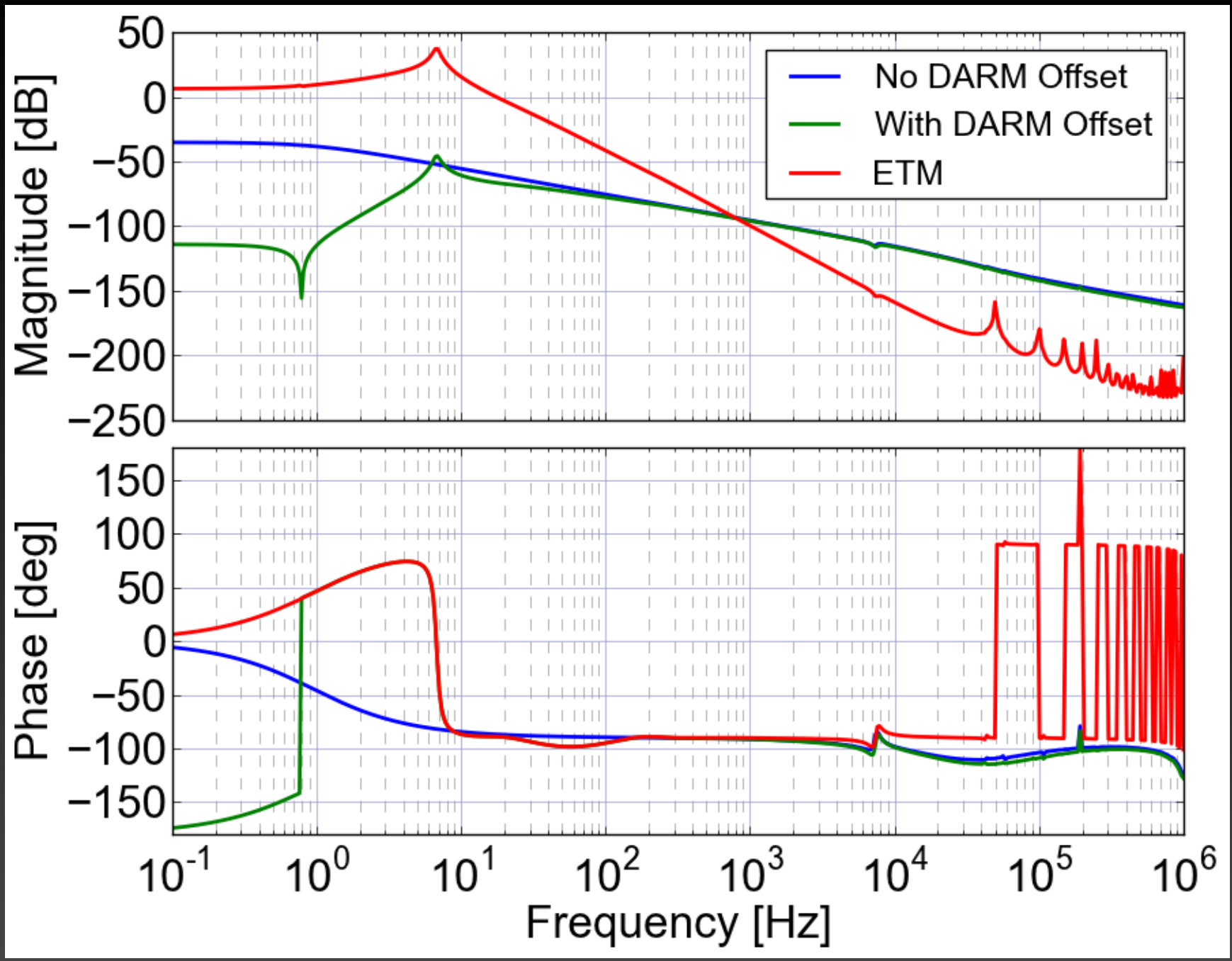


Flat Response <100kHz

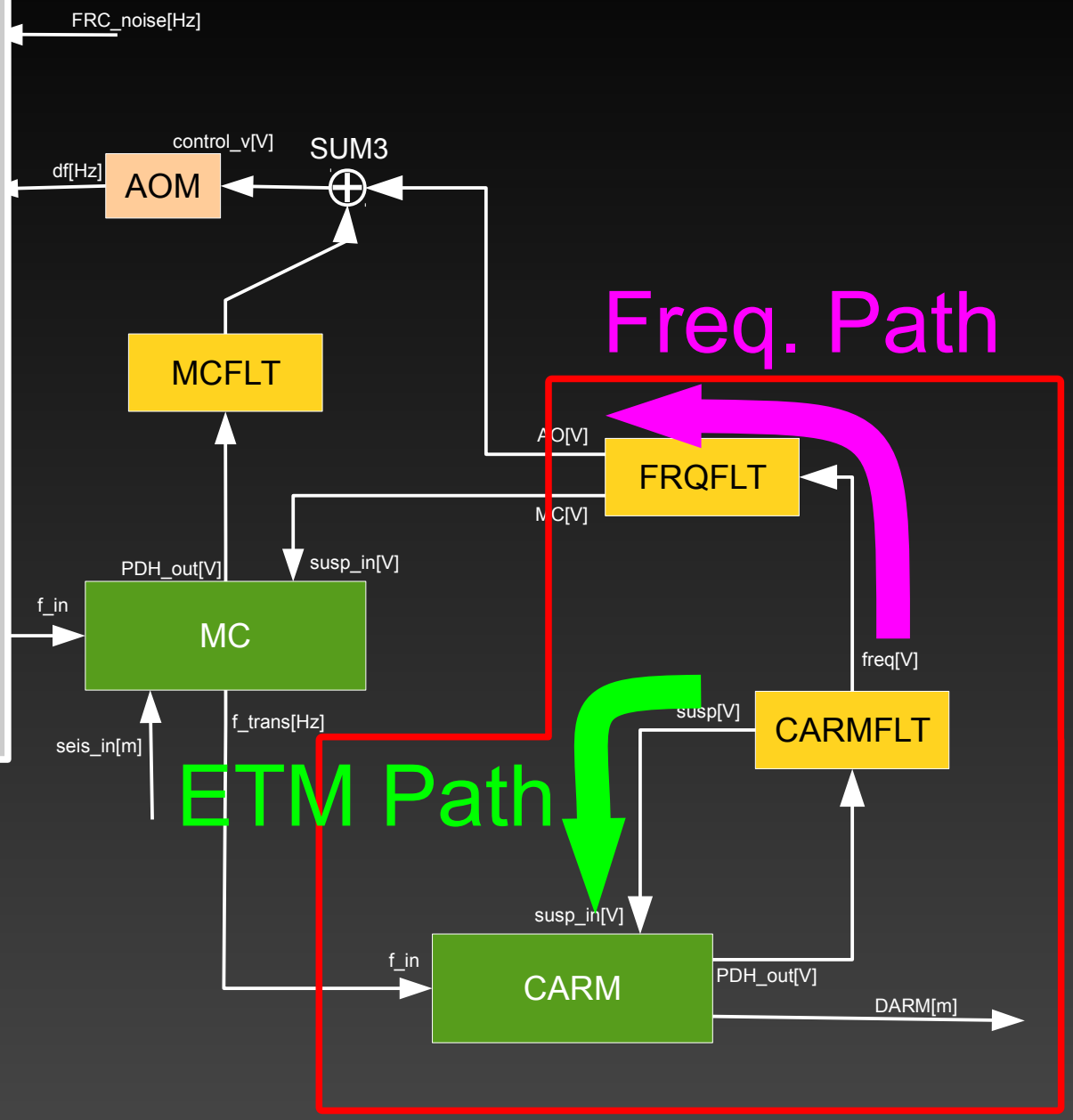



Magnitude [dB]
−20
−40
−60
−80
−100
−120
−140
−160
−180
Phase [deg]
150
100
50
0
−50
−100
−150
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
Frequency [Hz]

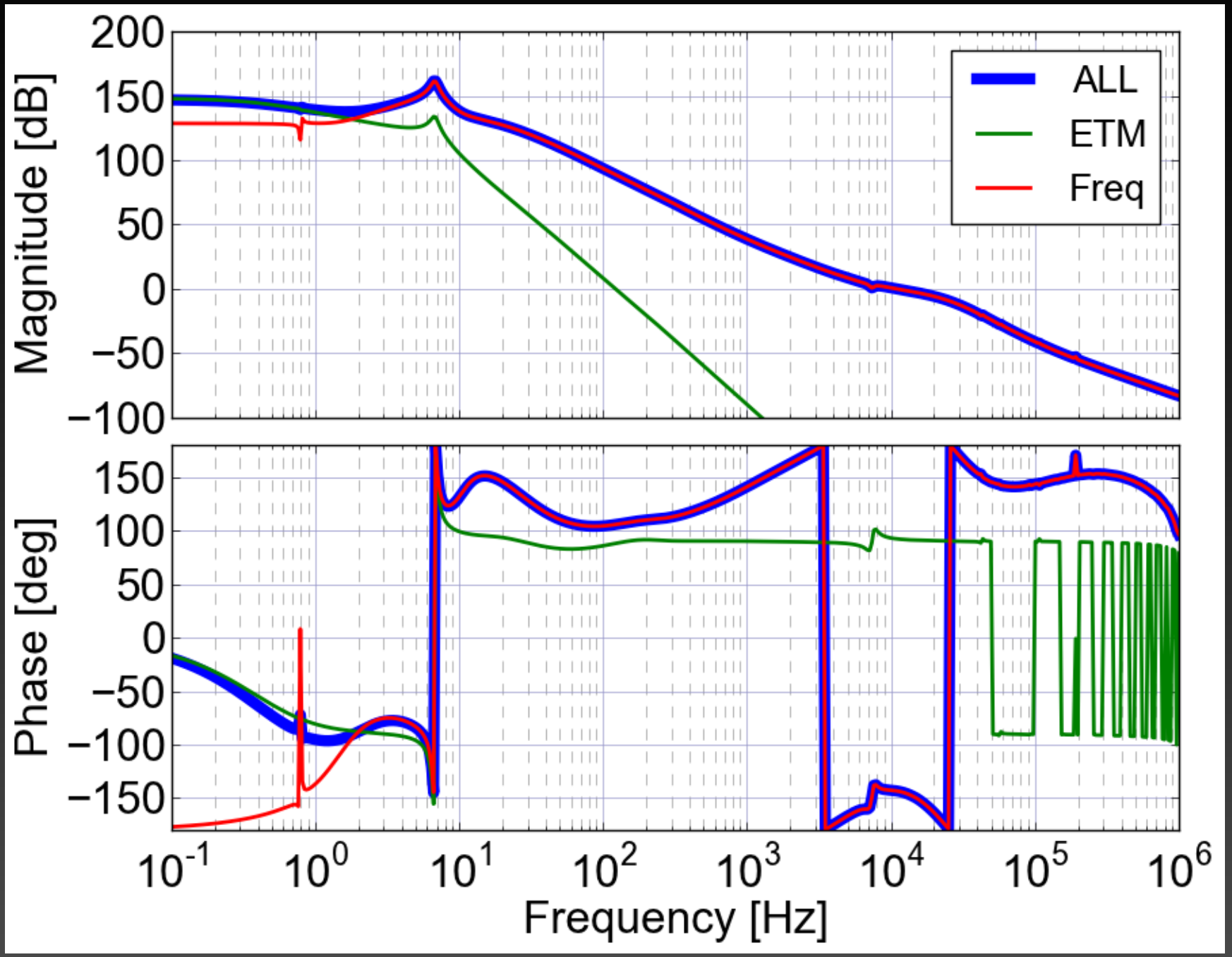

Magnitude [dB]
−20
−40
−60
−80
−100
−120
−140
−160
−180
No DARM Offset
With DARM Offset
Phase [deg]
150
100
50
0
−50
−100
−150
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
Frequency [Hz]

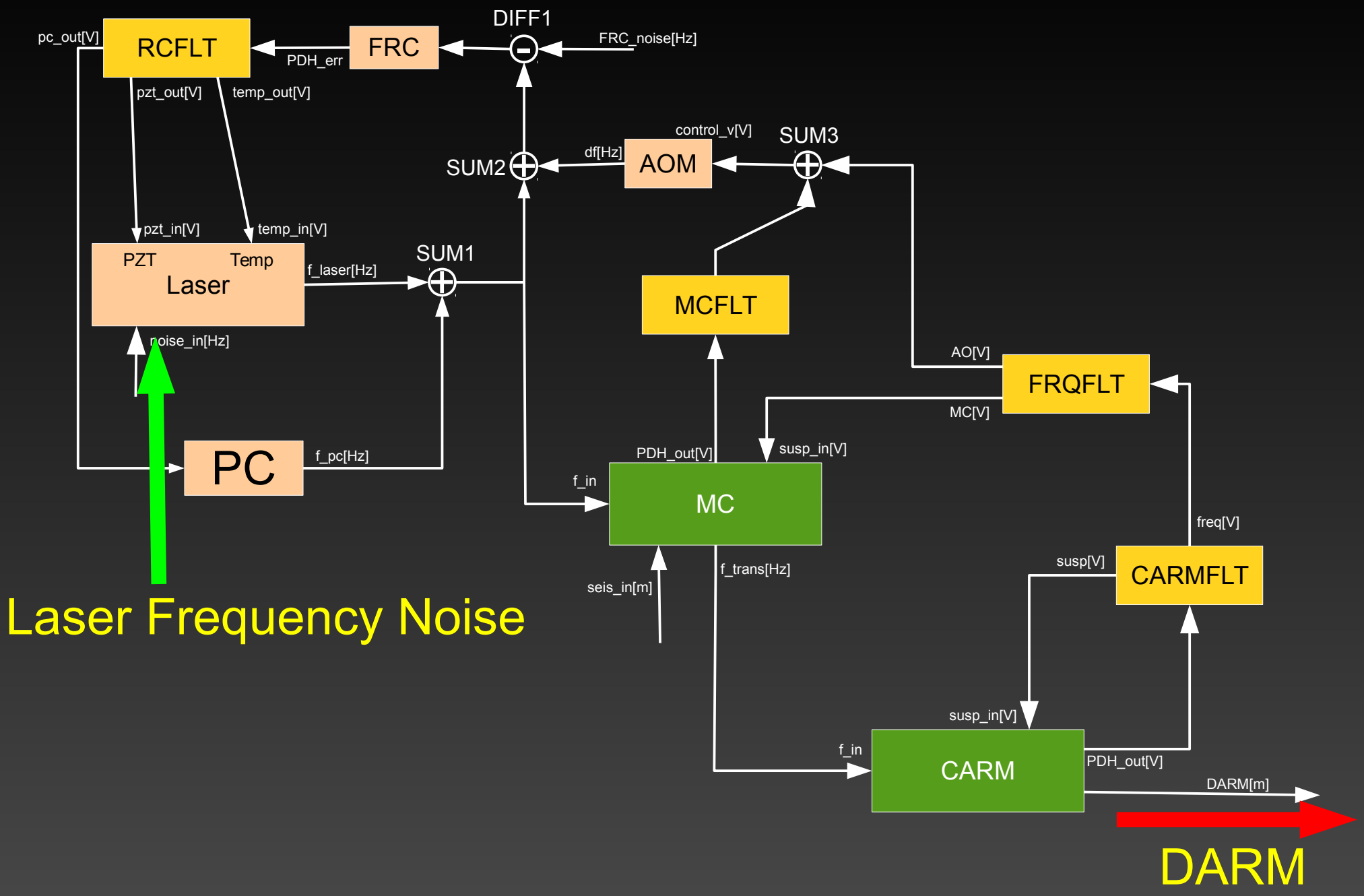

Magnitude [dB]
50
0
−50
−100
−150
−200
−250
No DARM Offset
With DARM Offset
ETM
Phase [deg]
150
100
50
0
−50
−100
−150
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
Frequency [Hz]

Flat Response <100kHz

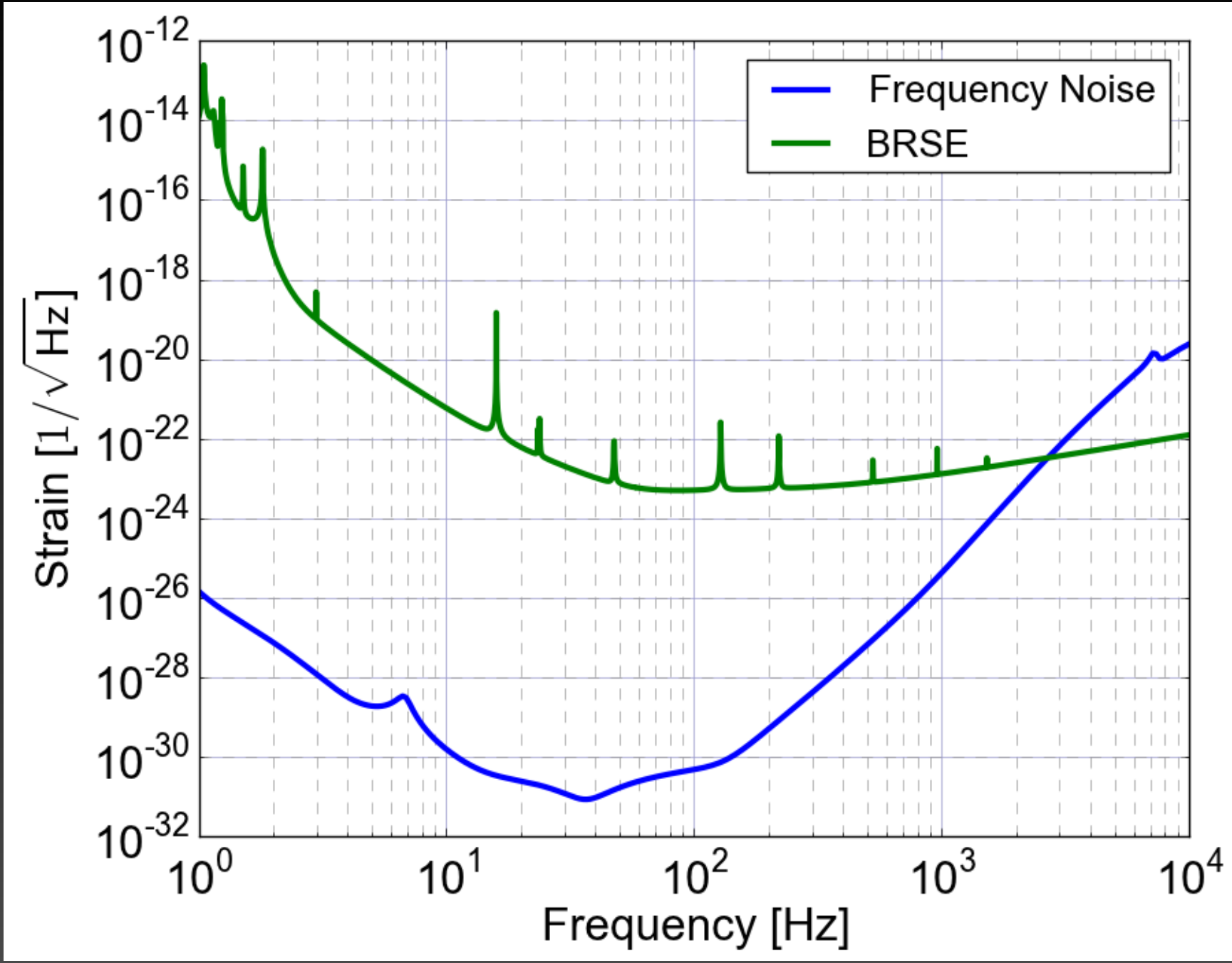


CARM Open Loop Gain

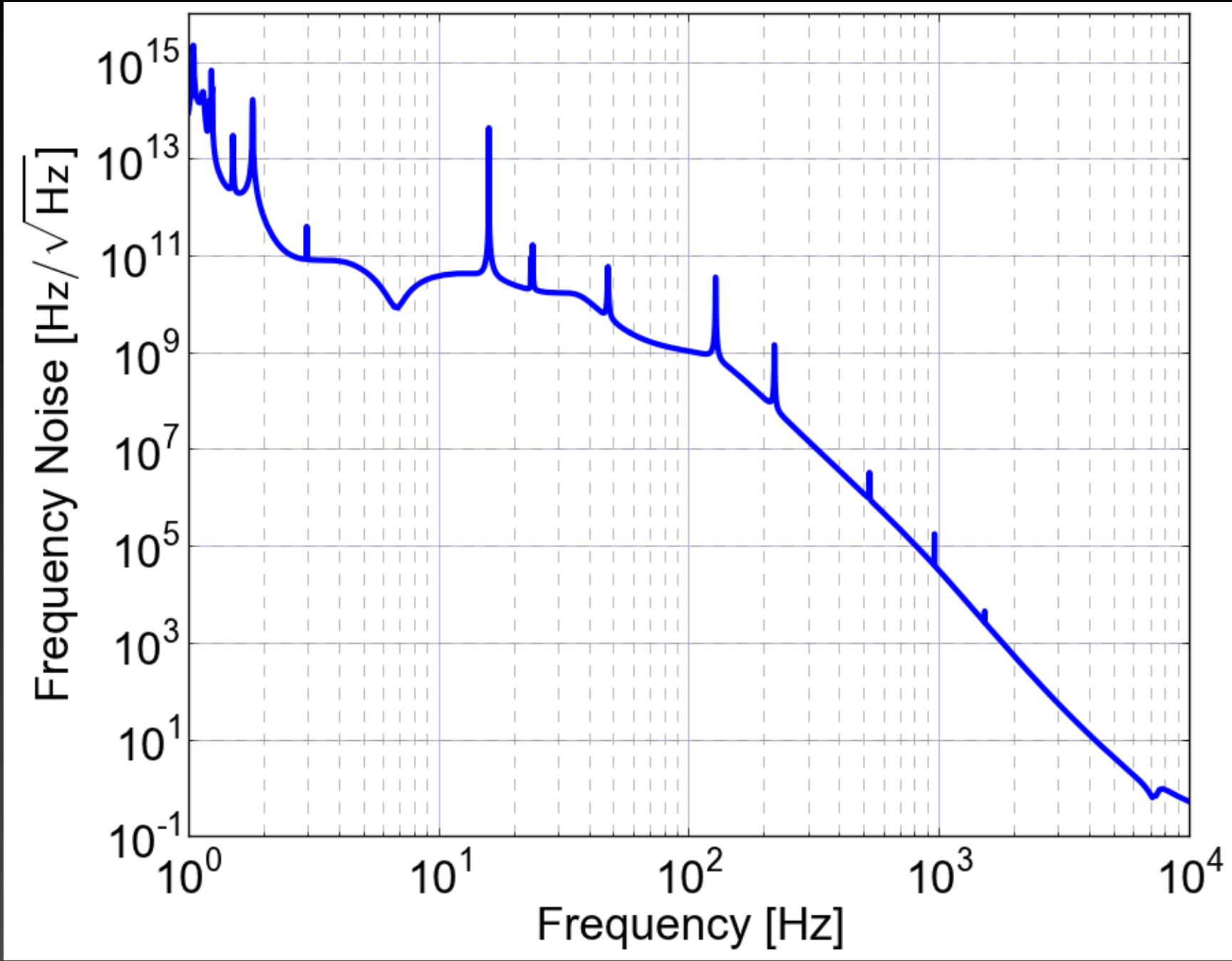


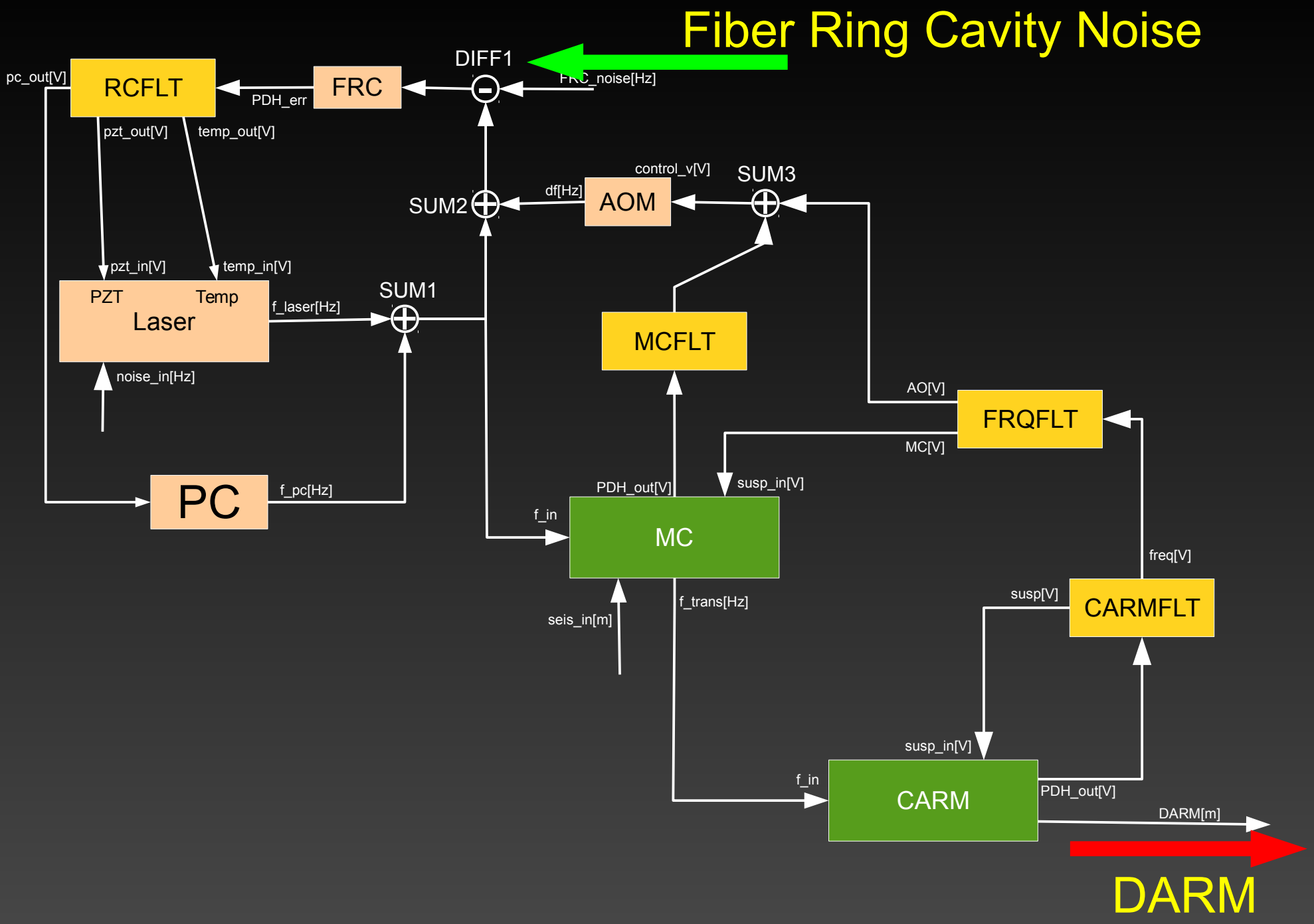

pc_out[V]
RCFLT
FRC
DIFF1
FRC_noise[Hz]
PDH_err
pzt_out[V]
temp_out[V]
control_v[V]
SUM3
df[Hz]
AOM
SUM2
pzt_in[V]
temp_in[V]
PZT
Temp
Laser
f_laser[Hz]
SUM1
MCFLT
noise_in[Hz]
AO[V]
FRQFLT
MC[V]
PDH_out[V]
susp_in[V]
PC
f_pc[Hz]
f_in
MC
freq[V]
susp[V]
CARMFLT
f_trans[Hz]
seis_in[m]
susp_in[V]
f_in
CARM
PDH_out[V]
DARM[m]
Laser Frequency Noise
DARM

Strain Equivalent Laser Noise (1kHz/rtHz flat)

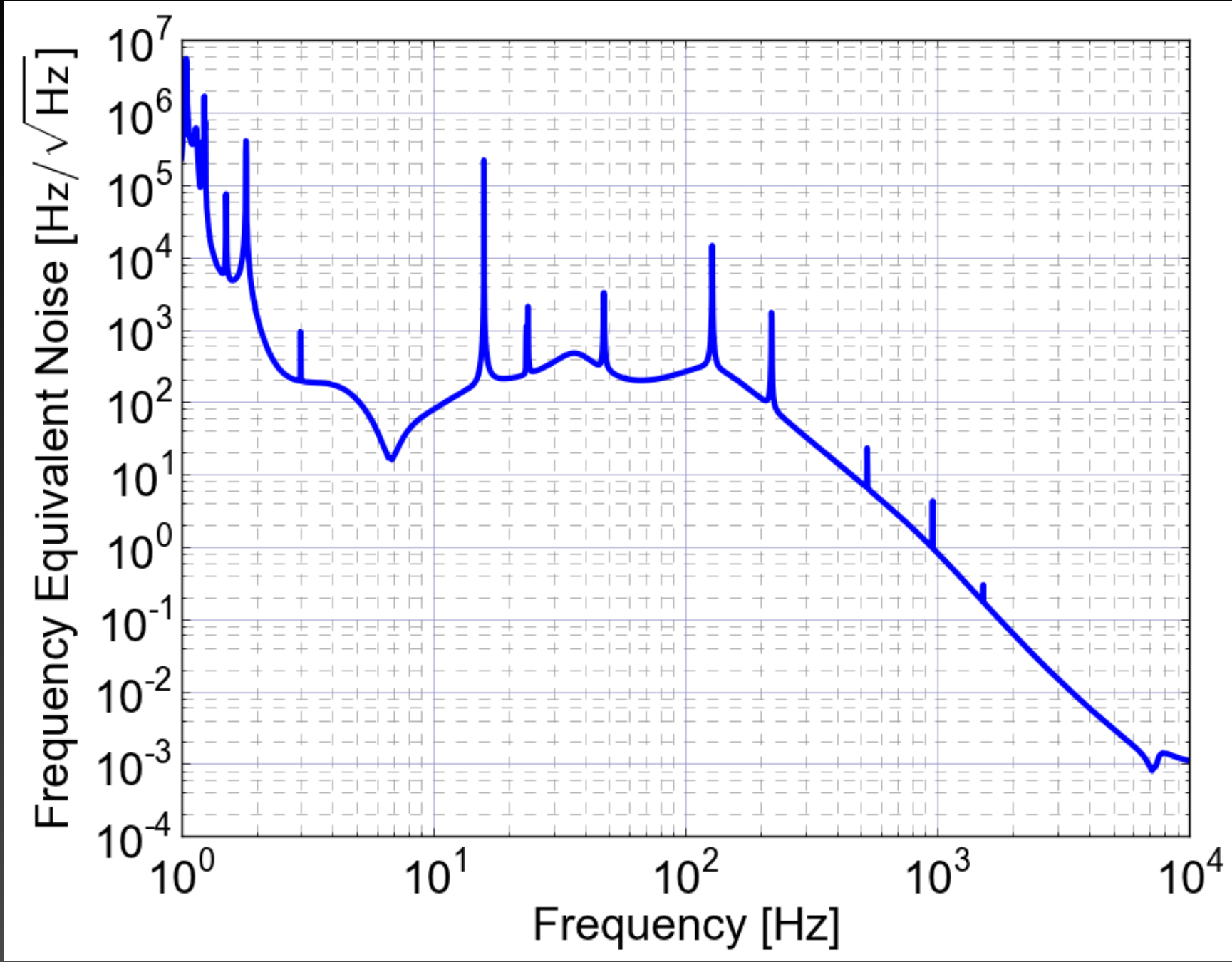


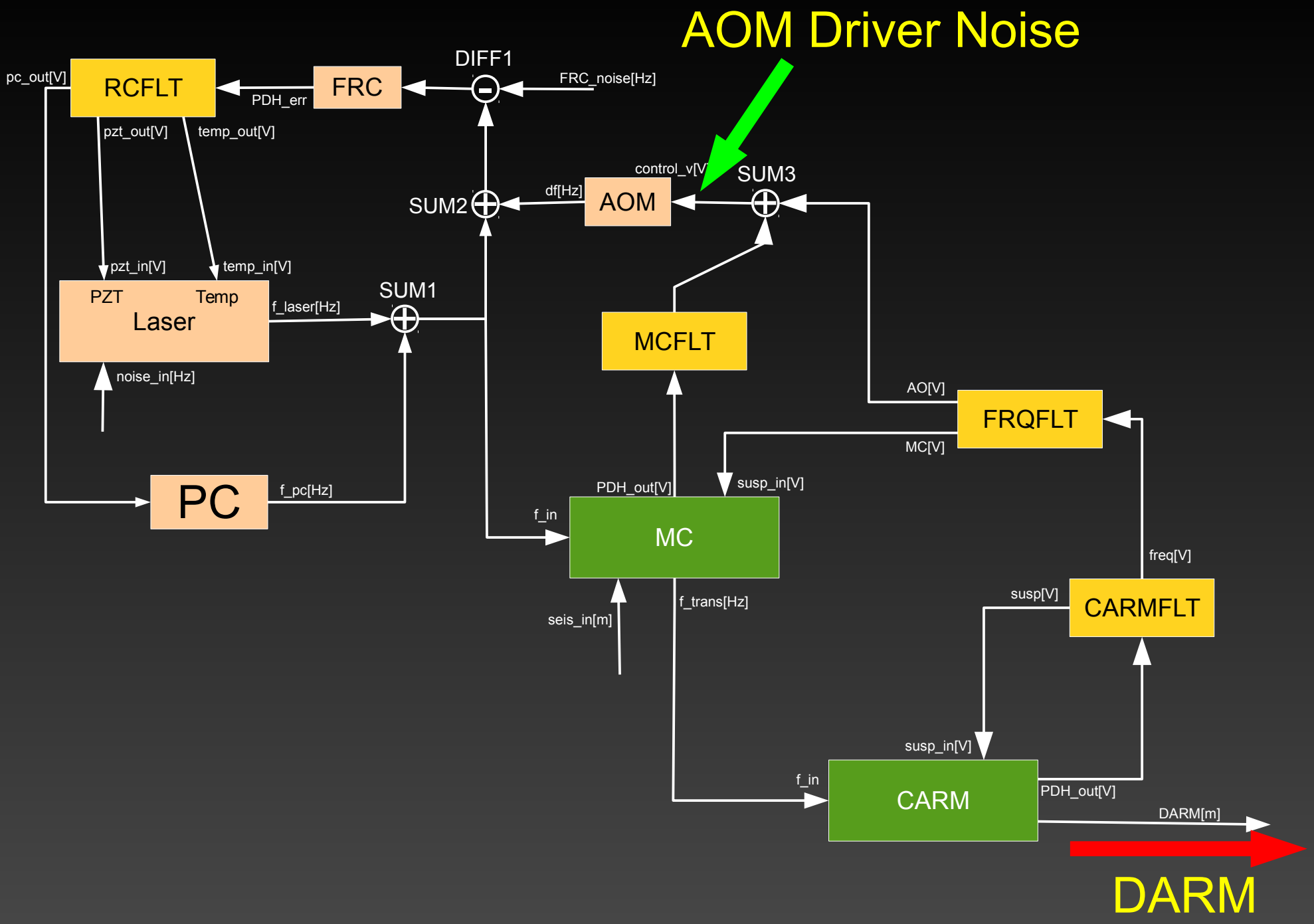
Frequency Noise Requirement



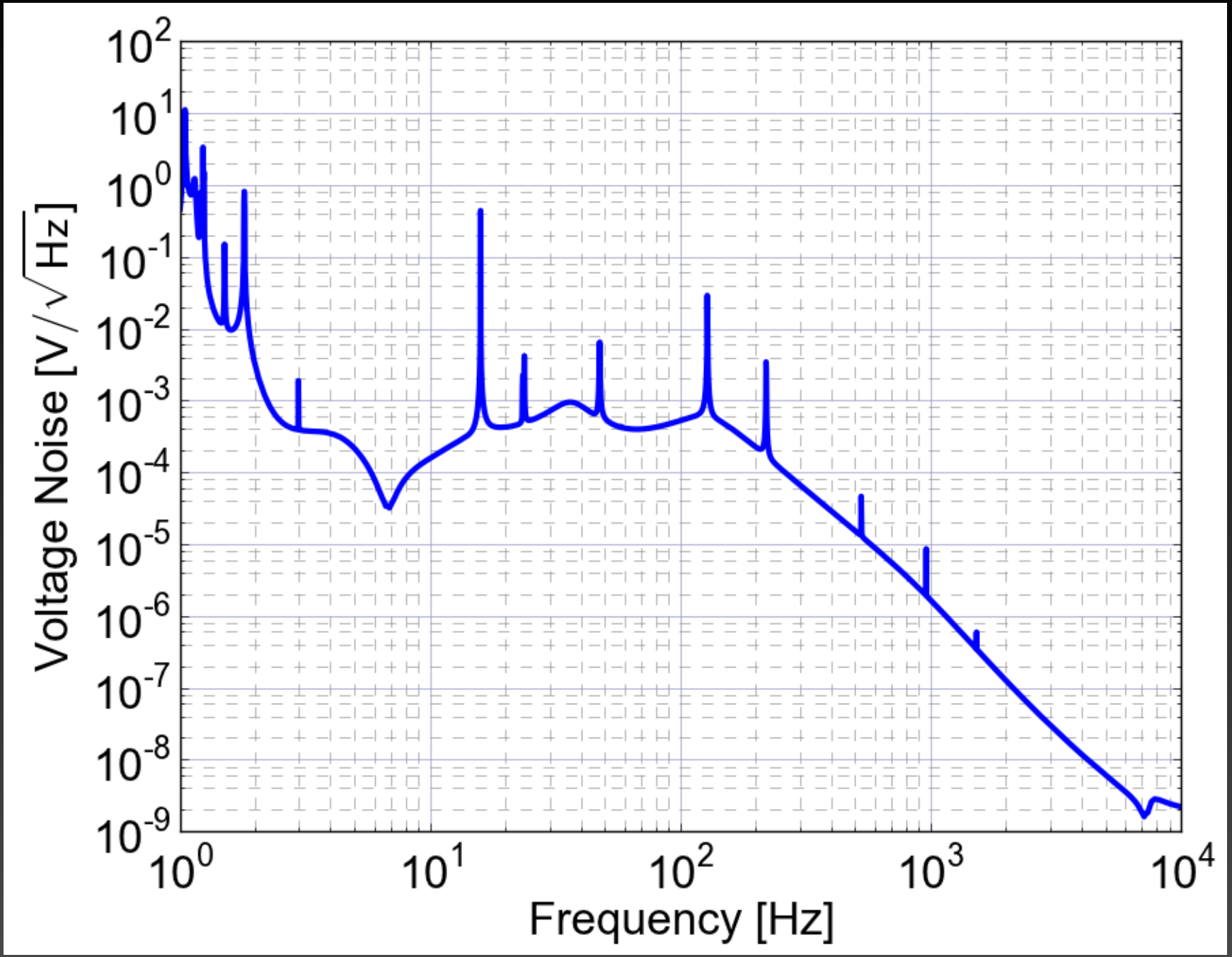

Fiber Ring Cavity Noise
DIFF1
FRC_noise[Hz]
pc_out[V]
RCFLT
FRC
PDH_err
pzt_out[V]
temp_out[V]
control_v[V]
SUM3
df[Hz]
AOM
SUM2
pzt_in[V]
temp_in[V]
PZT
Temp
Laser
f_laser[Hz]
SUM1
noise_in[Hz]
MCFLT
AO[V]
FRQFLT
MC[V]
PC
f_pc[Hz]
PDH_out[V]
susp_in[V]
f_in
MC
freq[V]
susp[V]
CARMFLT
seis_in[m]
f_trans[Hz]
susp_in[V]
f_in
CARM
PDH_out[V]
DARM[m]
DARM

Reference Cavity Noise Requirement




AOM Driver Noise
DIFF1
pc_out[V]
RCFLT
FRC
FRC_noise[Hz]
PDH_err
pzt_out[V]
temp_out[V]
control_v[V]
SUM3
df[Hz]
SUM2
AOM
pzt_in[V]
temp_in[V]
PZT
Temp
Laser
f_laser[Hz]
SUM1
noise_in[Hz]
MCFLT
AO[V]
FRQFLT
MC[V]
PC
f_pc[Hz]
PDH_out[V]
susp_in[V]
f_in
MC
freq[V]
susp[V]
CARMFLT
seis_in[m]
f_trans[Hz]
susp_in[V]
f_in
CARM
PDH_out[V]
DARM[m]
DARM

AOM Driver Noise Requirement



CLAVE

Easy Servo Design
& Detailed Noise Budget

TO DO

- Full IFO modeling
- Include better suspension models
- Include realistic electric circuits
- Automatic saturation detection
- GUI