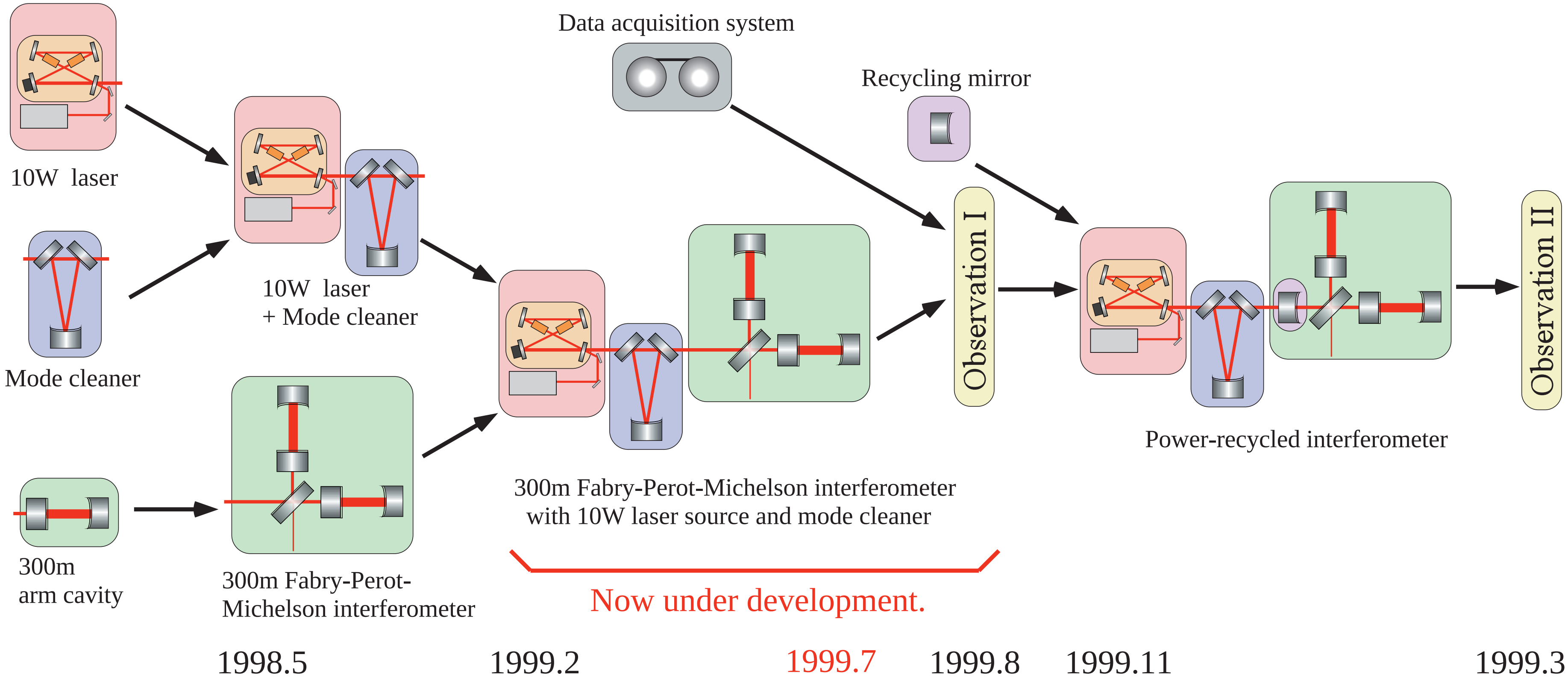
Development of the interferometer (1)

— Development steps of the TAMA300 interferometer —

- TAMA300 interferometer is developed step by step....



Development of the interferometer (2)

— First observation phase (Phase I) —

- First observation phase of TAMA300 (**Phase I**).
  - · Start in August, 1999.
  - · Operate almost the whole interferometer.
    - · 10 W laser source with 10 m mode cleaner.
    - · Main interferometer with 300 m arm cavities.
    - · Without power recycling.
  - · Sensitivity — $h \sim 3 \times 10^{-20}$.

$$\Rightarrow \text{Displacement noise} < 5 \times 10^{-19} \quad \text{m}/\sqrt{\text{Hz}}.$$
$$\text{Laser frequency noise} < 1 \times 10^{-6} \quad \text{Hz}/\sqrt{\text{Hz}}.$$

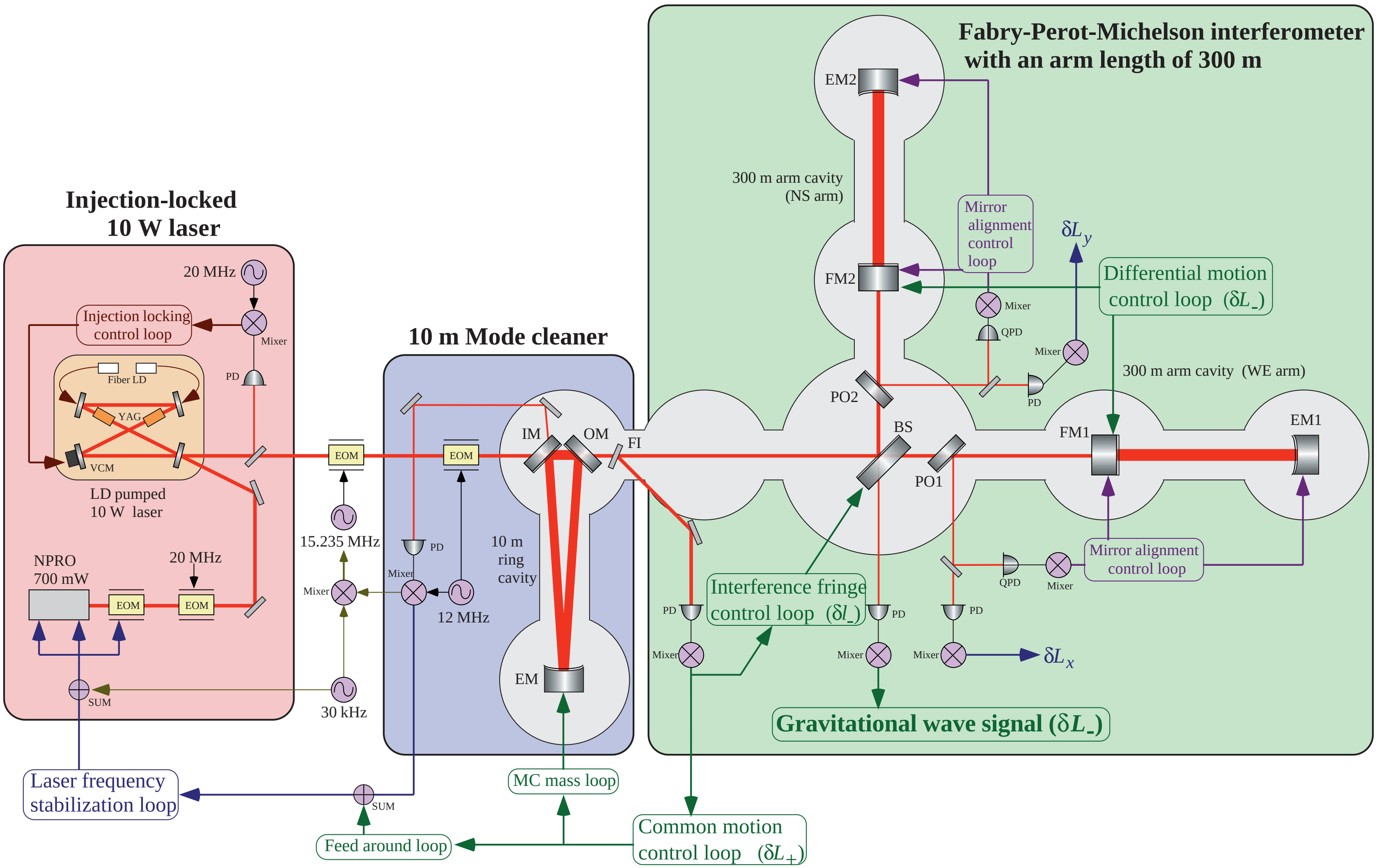
$$\Downarrow$$

- **Developing the interferometer**.

  — The interferometer is **operated with the final configuration.**

Development of the interferometer (3)

— TAMA300 interferometer for Phase I —

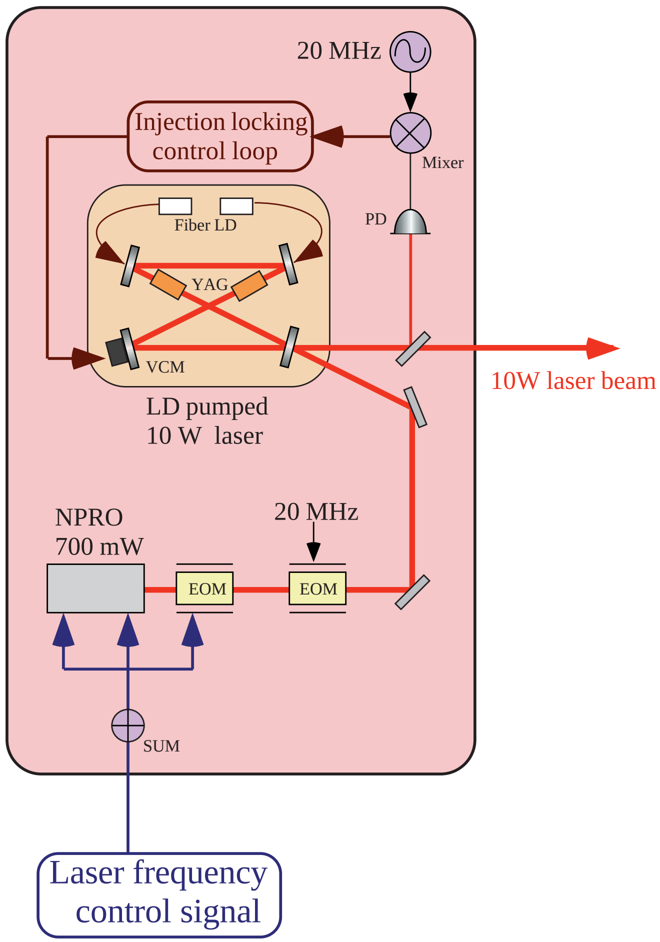


10-W laser source (1)

— Features —

- **Injection-locked Nd:YAG laser.**
  - Output power of 10 W.
  - Master laser
    - LD-pumped Nd:YAG laser (700 mW).
    - Frequency-controlled with
      Thermal control, PZT, External EOM.
  - Slave laser
    - Fiber LD-pumped ring laser.
    - Injection-locked to the master laser
      with a VCM (Voice Coil Motor).
    - Error signal is extracted
      using 20 MHz phase modulation.
  - Intensity stabilization
    - Controlled with an external EOM.

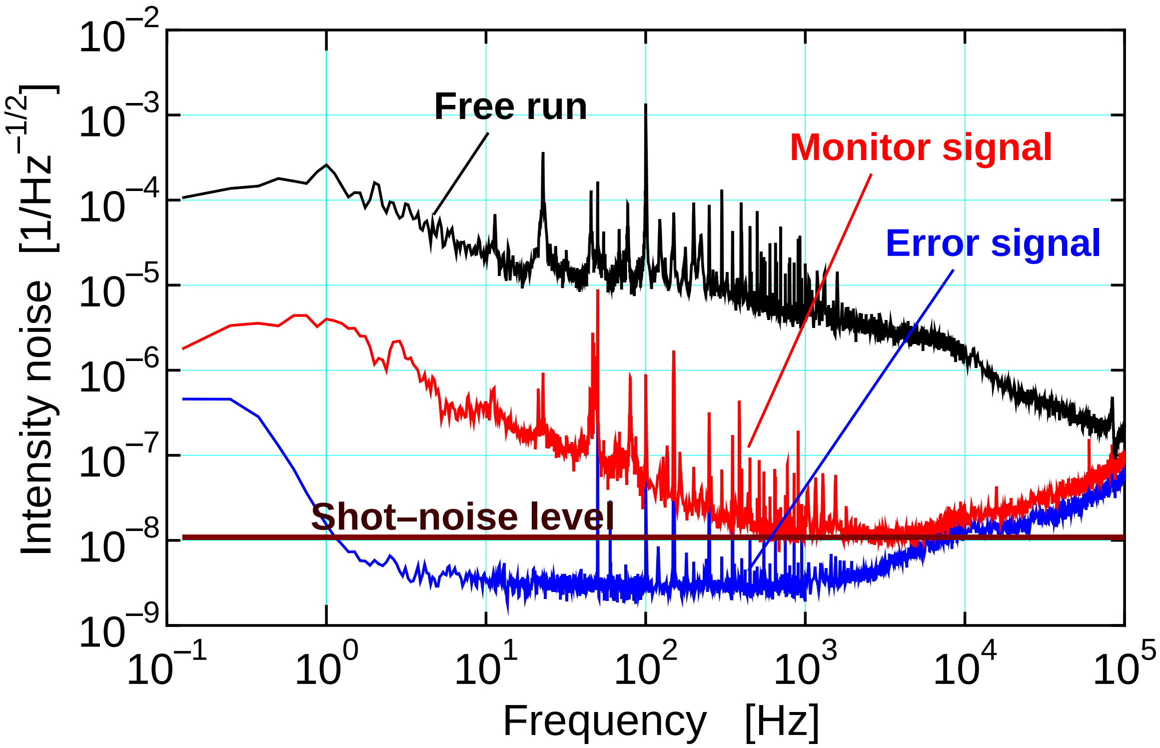
Injection-locked 10 W laser



10-W laser source (2)

— Intensity stabilization —

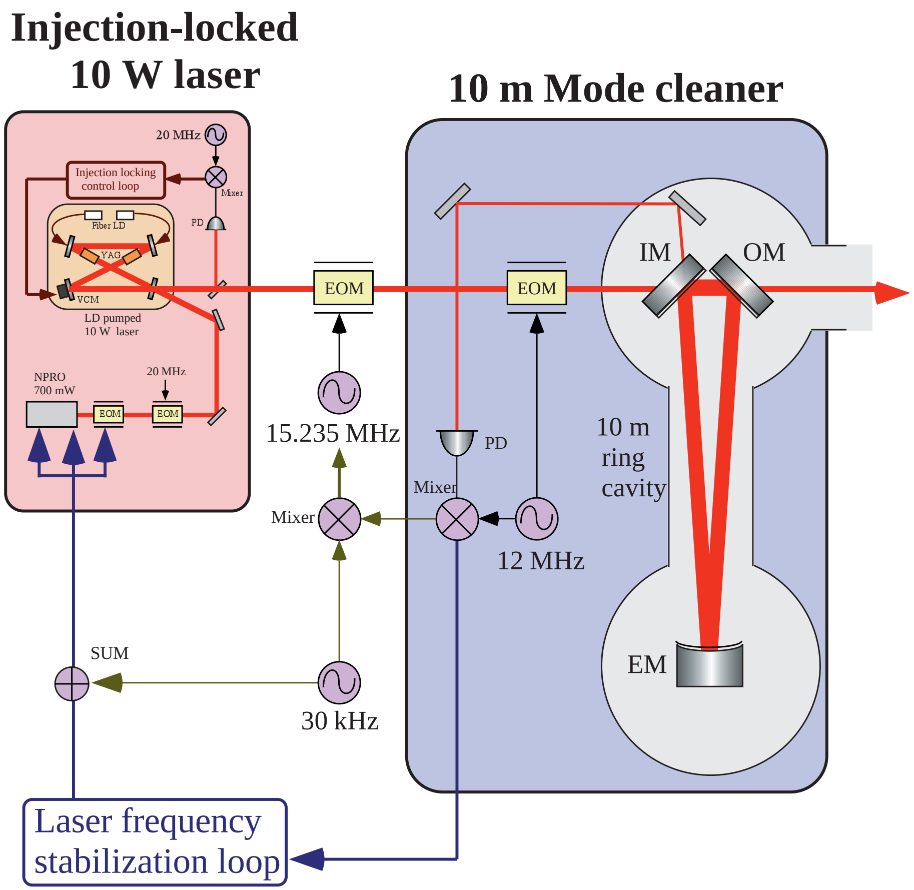
- Intensity noise is stabilized using an EOM.
  — stabilized to $2 \times 10^{-8} \quad 1/\sqrt{\mathrm{Hz}}$.



10-m mode cleaner (1)

— Features —

- **10-m ring cavity.**
  - · Three mirrors
    - — Independently suspended (double pendulum).
  - · Finesse — 1,700.
  - · Transmissivity — 54%.
- Length control
  - · Error signal — extracted using 12 MHz phase modulation, fed back to to laser source.
- Transmission of the modulation sidebands.
  - · FSR = Modulation freq. (15.235 MHz).
  - · Error signal
    - — extracted using additional modulation.



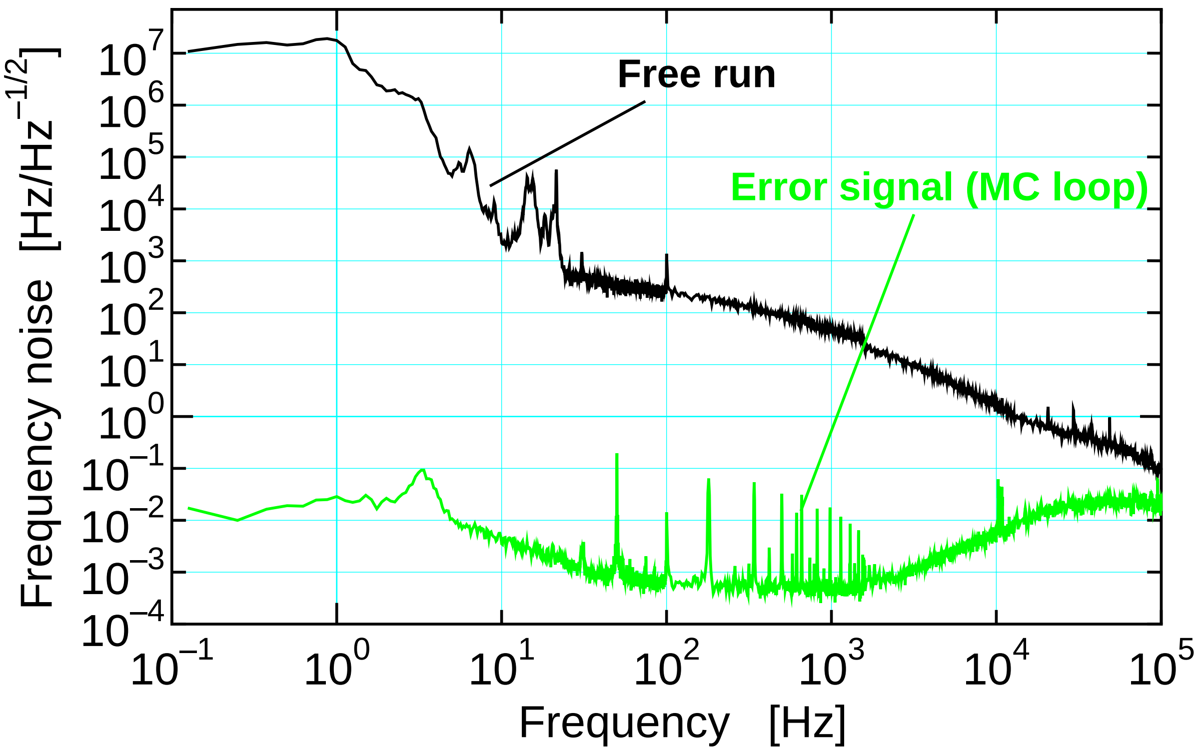
10-m mode cleaner (2)

— Frequency stabilization —

- Laser frequency noise

  — pre-stabilized using the 10-m mode cleaner.

  $\rightarrow$ stabilized to $5 \times 10^{-4}\ \ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$.



10-m mode cleaner (2)

— Transmission of the modulation sidebands —

- Phase modulator

  for the control of the main interferometer

  · Placed before the MC.

  $\rightarrow$ reduce the wave-front distortion.

  · Modulation frequency (ν_{mod})

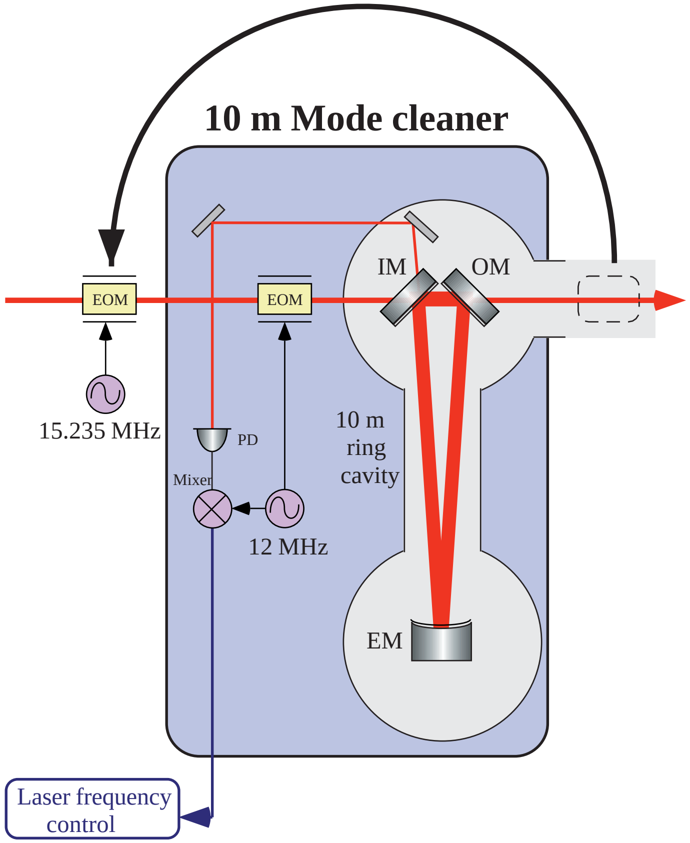
  — equal to the FSR of the MC (ν_{FSR}).

  $\Downarrow$

  · Modulation sidebands pass through the MC.

  · Cause excess noise

  without fine adjustment of ν_{mod}.

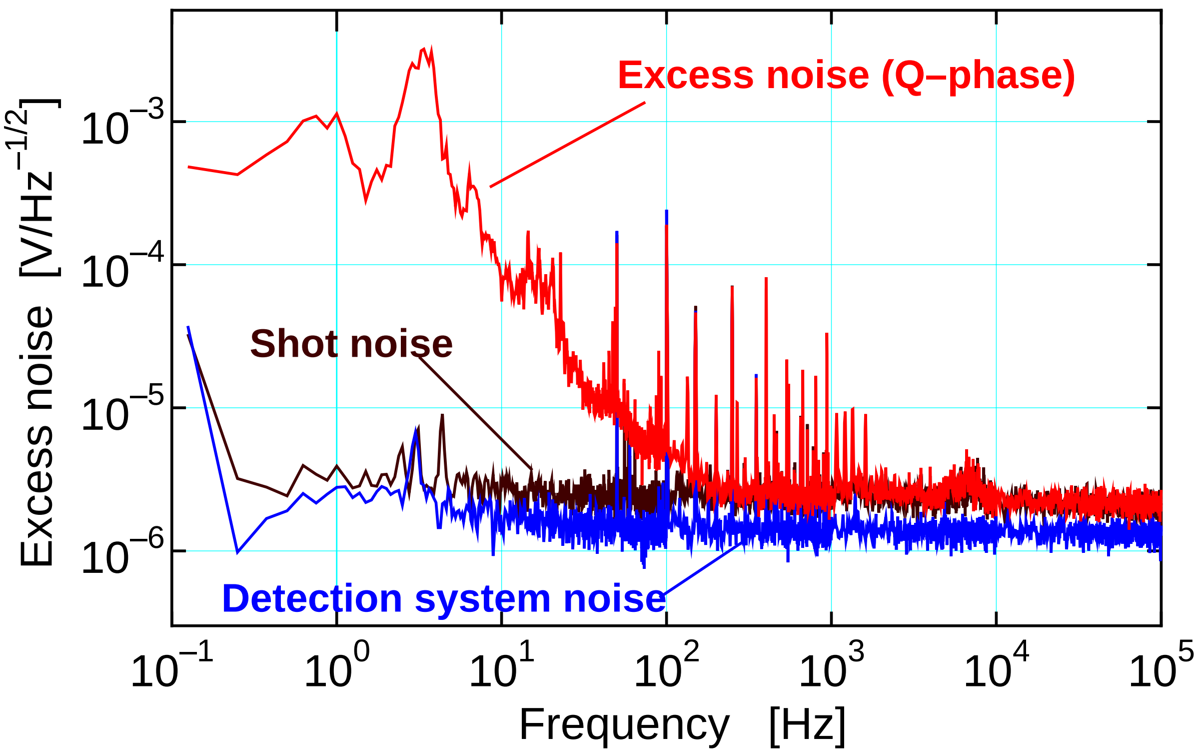


10-m mode cleaner (3)

— Excess noise —

- Adjust the modulation freq. equal to the FSR of the MC.

(the difference — below 10 Hz)

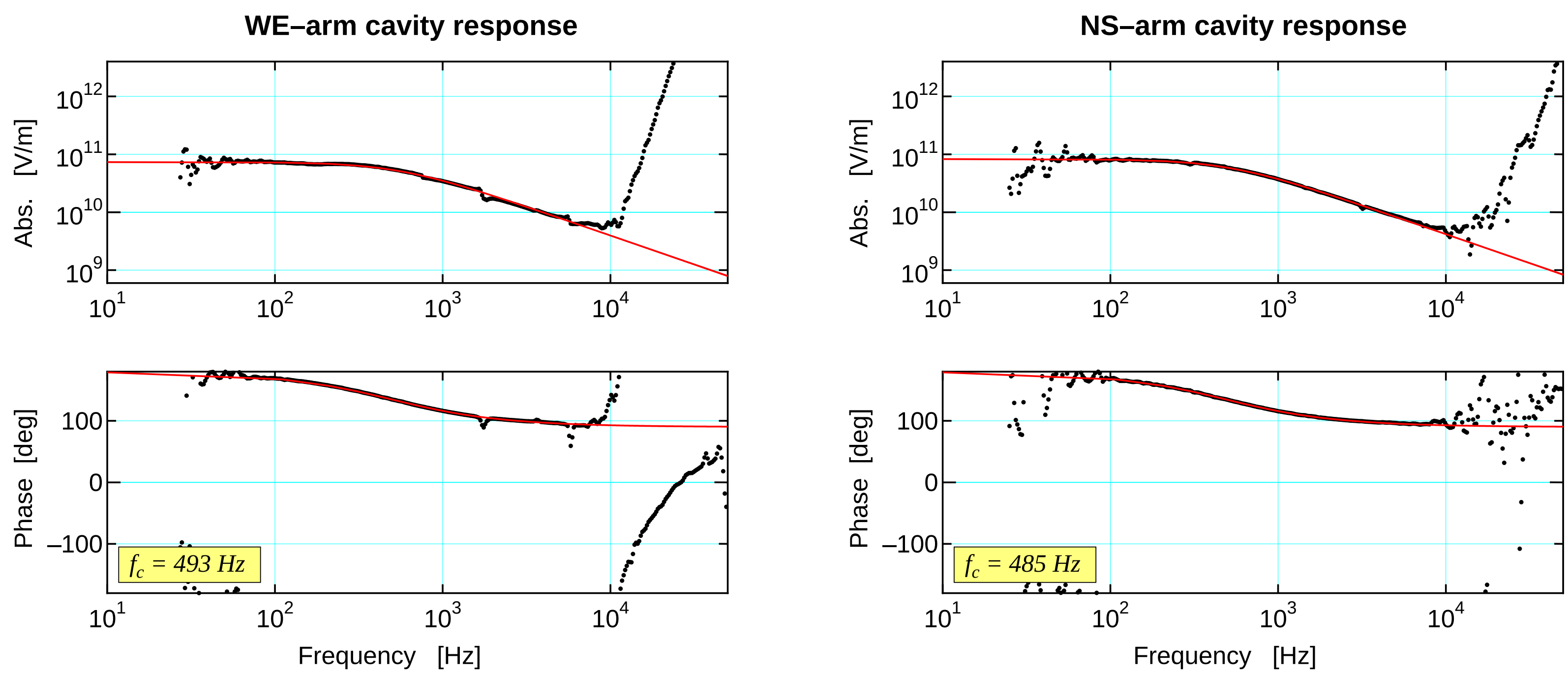


- Excess noise is below the shot noise level (30 mA).

300-m arm cavity (1)

— Features —

- 300-m Fabry-Perot arm cavities
  - · Finesse — 516.
  - · Cut-off frequency — 480.
  - · Alignment control system (Wave-front sensing scheme).

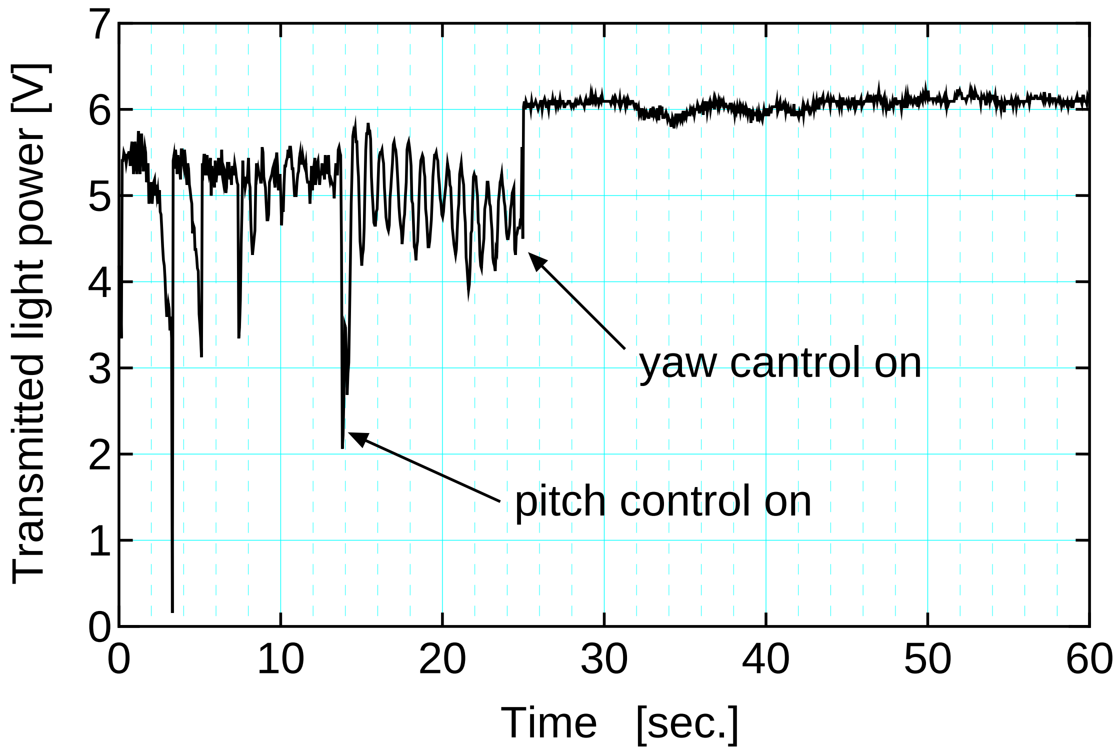


300-m arm cavity (2)

— Alignment control —

- Operated stably with the alignment control system.

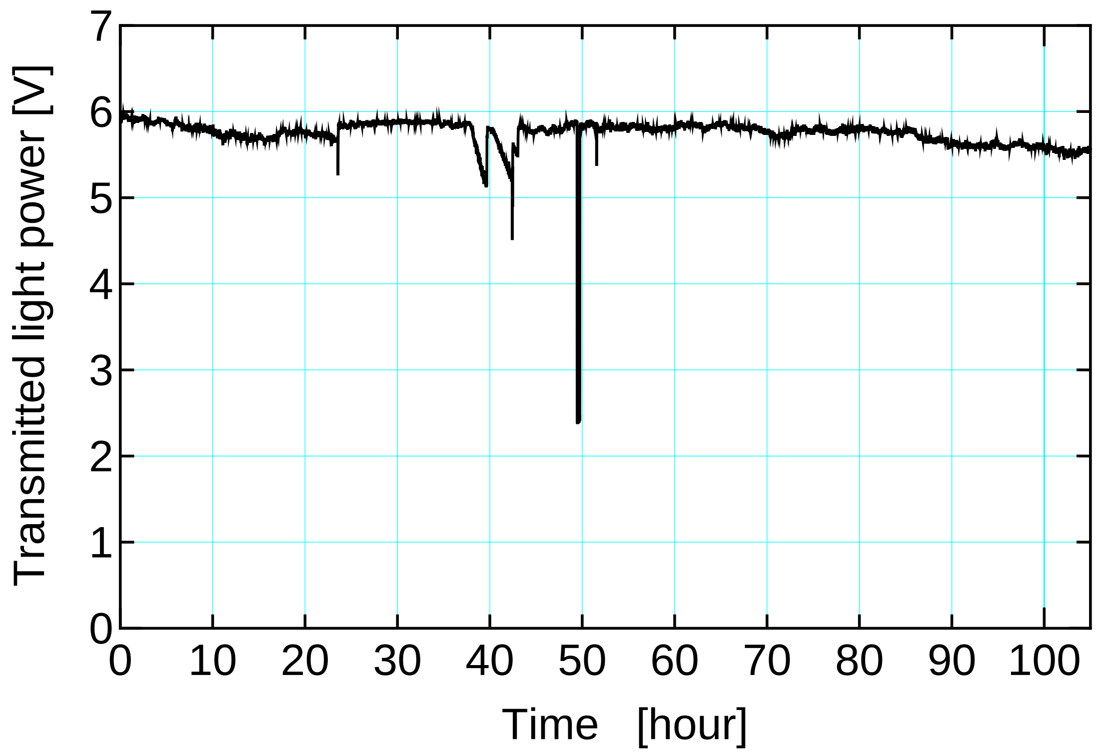
  Four degrees of freedom are controlled for each arm cavity.



300-m arm cavity (3)

— Long term operation —

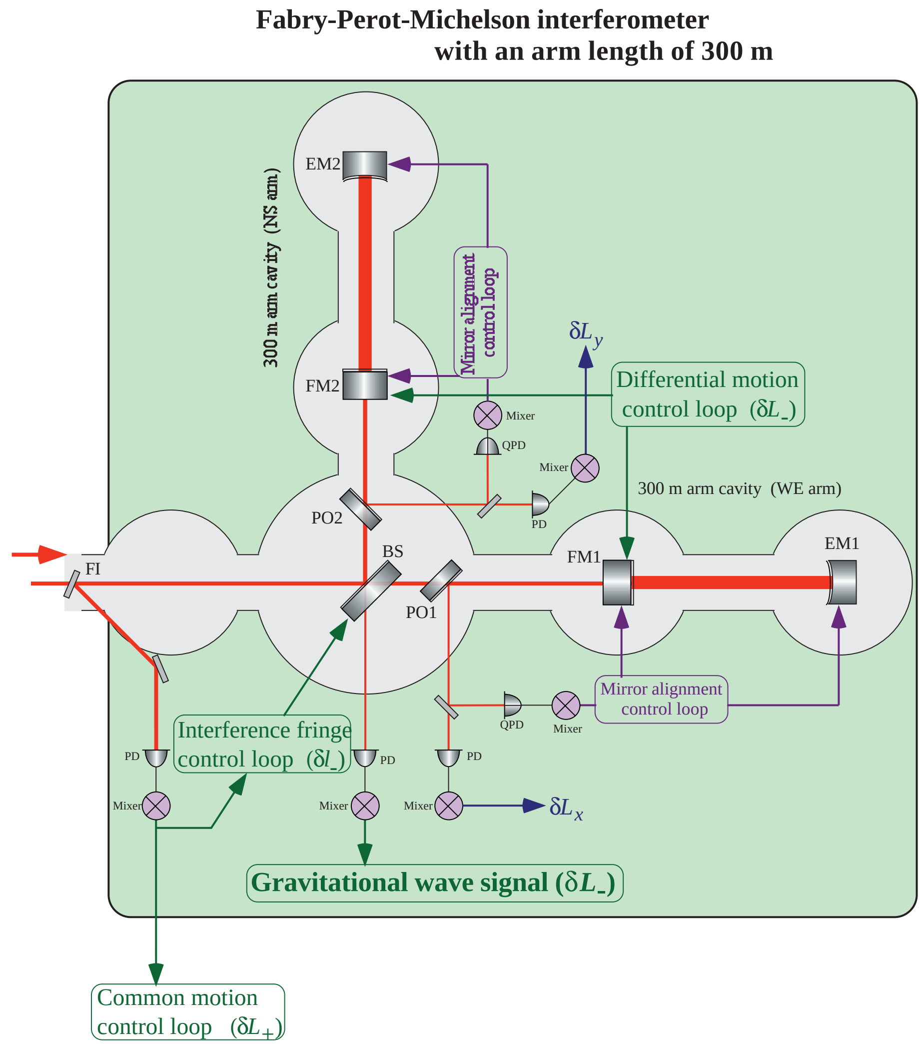
- One arm cavity — operated about 4 days without unlock.
  - · Laser source — 700 mW NPRO.
  - · With alignment control.



Main interferometer with the 300-m arm cavities (1)

— Features —

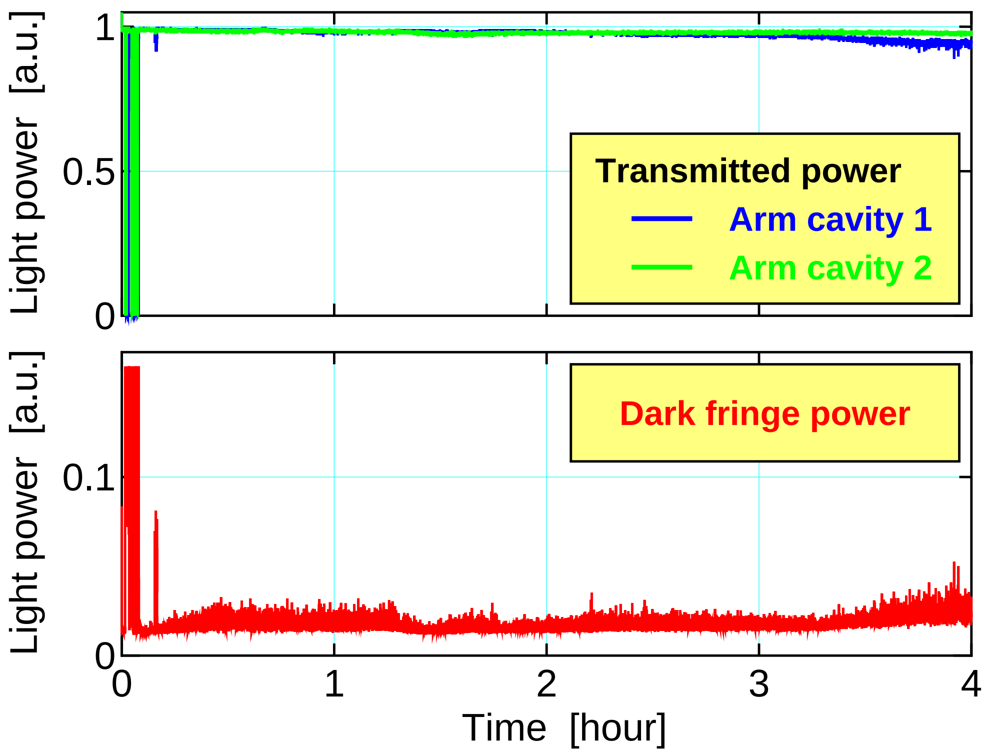
- Michelson interferometer with the 300-m Fabry-Perot arm cavities.
  - Finesse — 516.
  - Cut-off frequency — 480.
- Controlled with the frontal modulation scheme.
  - δL_- signal — fed back to the front mirrors (diff.).
  - δl_- signal — fed back to the beam splitter.
  - δL_+ signal — fed back to the laser and the MC.
- Alignment control system.
  - Wave-front sensing scheme.
  - Sample small power with pick-off mirrors.



Main interferometer with the 300-m arm cavities (2)

— Operation of the main interferometer —

- Main interferometer — operated over 4 hours.
  - · Laser source — 700 mW NPRO.
  - · With alignment control.



TAMA300 interferometer (1)

— Operation of the whole interferometer —

- TAMA300 interferometer is

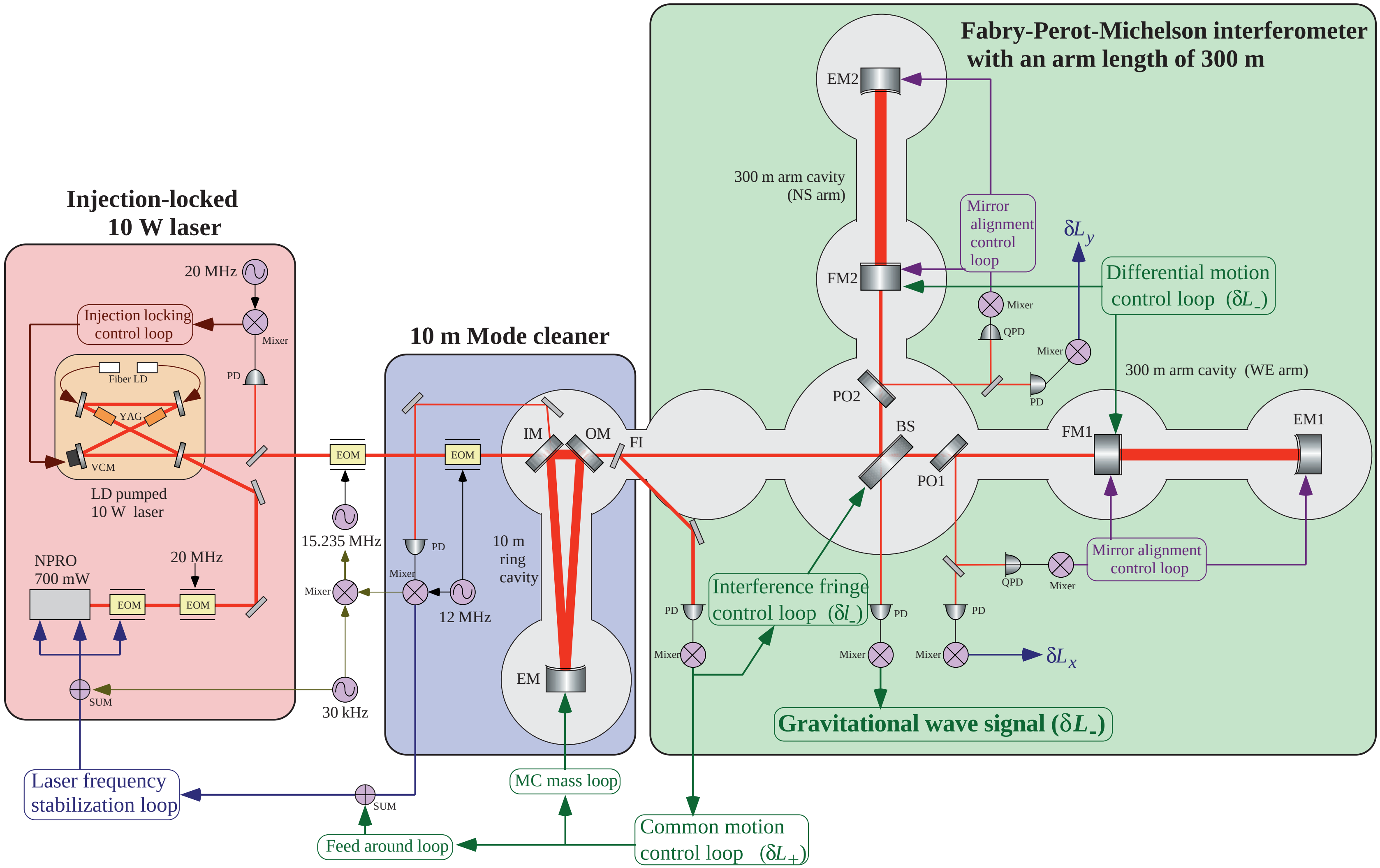
  operated under the Phase I configuration.

  - 10 W laser source.
    - Frequency of the master laser

      — controlled with the error signals of the MC and the interferometer.
    - Slave laser — injection-locked to the master laser.
  - 10 m ring mode cleaner.
    - Pre-stabilize the laser frequency.
    - Transmission of the modulation sidebands.
    - Length is controlled with the δL_+ signal of the interferometer.
  - Main interferometer with the 300 m arm cavities.
    - Controlled with the frontal modulation scheme.
      - δL_- signal — differentially fed back to the front mirrors.
      - δl_- signal — fed back to the beam splitter.
      - δL_+ signal — fed back to the laser and the MC.
    - Alignment control for the arm cavities.
    - **Without power recycling**.

TAMA300 interferometer (2)

— TAMA300 interferometer for Phase I —



TAMA300 interferometer (3)

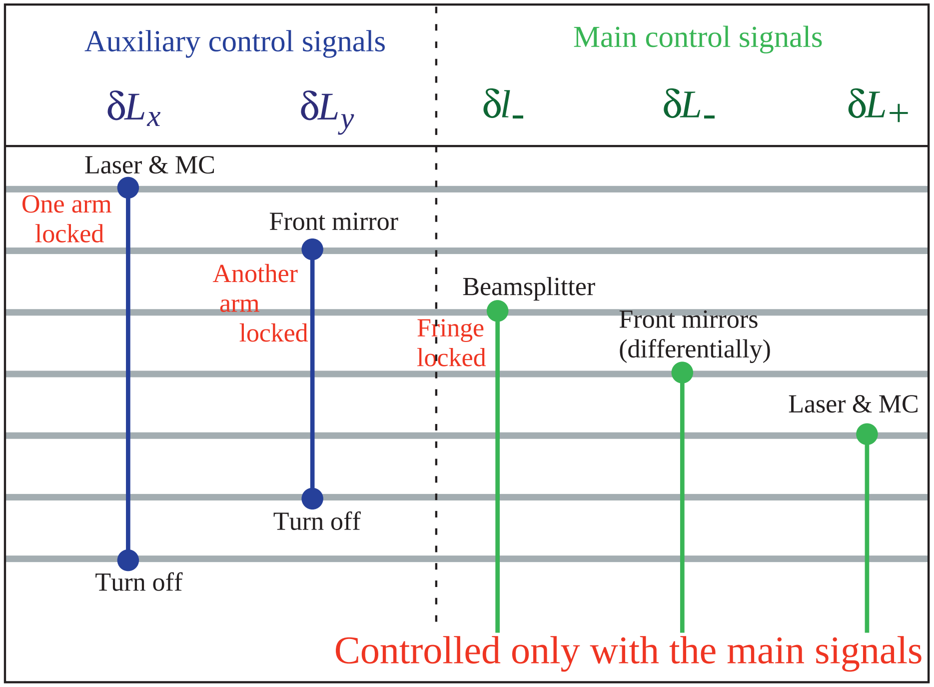
— Lock acquisition —

- Difficult to acquire the lock of the interferometer
  only with the main control signals.

  ⇓

  Use auxiliary control signals.

  extracted from the sampled beams from the pick-off mirrors.

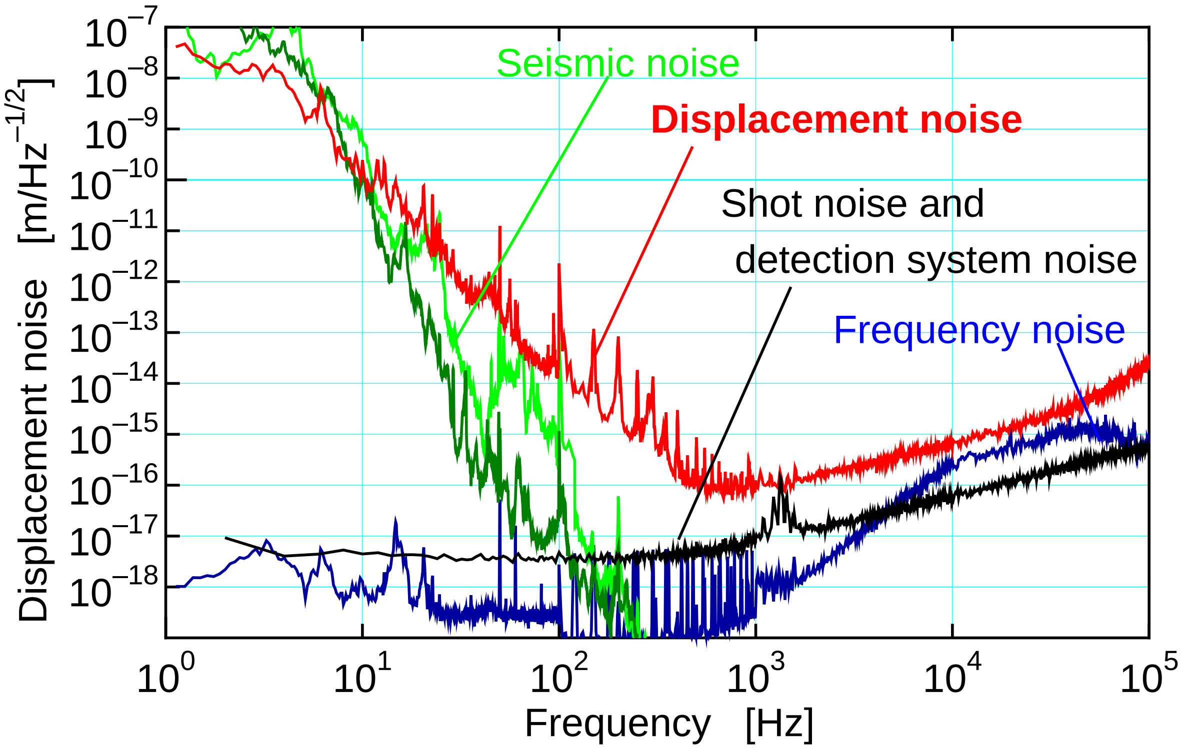


TAMA300 interferometer (4)

— Displacement noise level of the TAMA300 interferometer —

- Preliminary sensitivity.

  Displacement noise level — 1×10^{-16} m/$\sqrt{\text{Hz}}$.



- Stability — operated over one hour.

TAMA300 interferometer (5)

— Noise sources and problems —

- Noise sources.
  - · ~30 Hz — seismic noise.
  - · ~500 Hz — alignment control system noise.
  - · 500 Hz ~ — noises due to electronic circuits.
- Poor contrast and CMRR.

  Contrast — 95.4%, CMRR — 44.

  Probably, because of insufficient mode matching and alignment.

  ⇓

  Changed the mode-matching telescope

  between the MC and the main interferometer.

  ⇓

  Mode matching — 97.8% → 99.8%.

Summary and future works

- The TAMA300 interferometer is
  operated with the final control configuration for the Phase I observation.
  - Sensitivity $\sim 1 \times 10^{-16}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$.

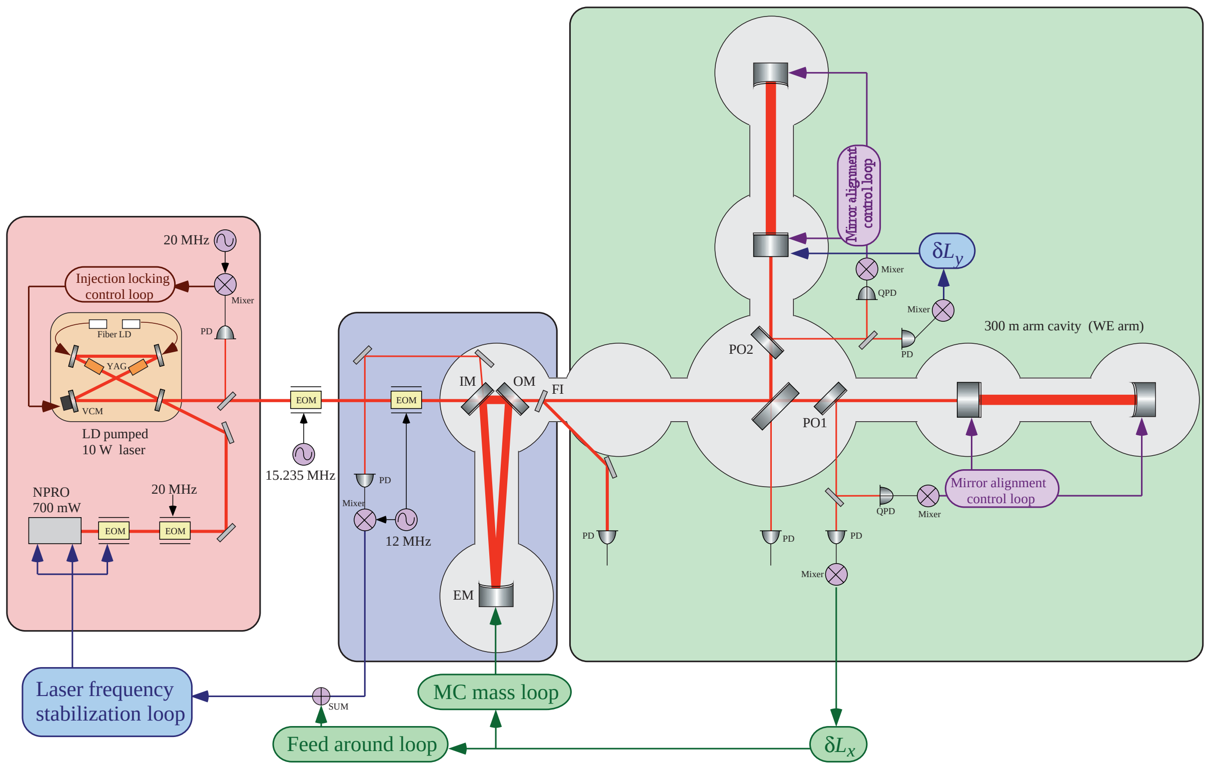
$$\Downarrow$$

- **Improve the sensitivity** $\rightarrow 5 \times 10^{-19}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$.
  - Incident full laser power onto the PDs $\rightarrow$ improve the shot noise and detection system noise level.
  - Optimize the alignment filter $\rightarrow$ reduce the alignment control system noise.
  - Change the mode-matching telescope $\rightarrow$ improve the contrast and the CMRR.
- Realize stable operation.
  - Low frequency drift control (beam pointing, beam centering, modulation frequency, ...).
  - Improvement of the environment (vibration due to vacuum pumps, ...).
- Data-acquisition and analysis.
  - Data-acquisition system.
  - Calibration.
  - Data analysis.

Locked-Fabry-Perot configuration (1)

— Optical and control configuration —

- **Operate the both arm cavities** with the 10 W laser source.
- Locked Fabry-Perot configuration.



Locked-Fabry-Perot configuration (2)

— Noise level —