Commissioning, Part II

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Where do we go from here?

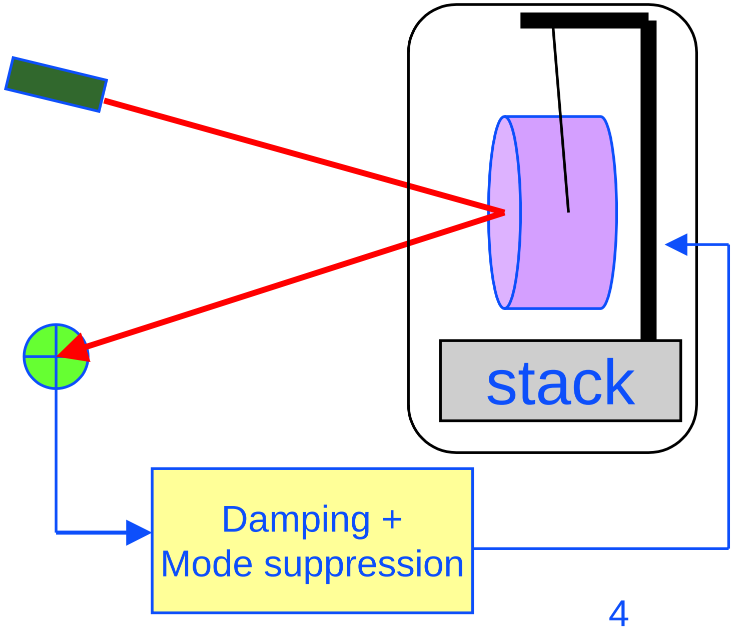
- Stability & robustness improvements
  - Acquisition time and lock duration
  - Residual fluctuations (mostly power) while in lock
- High frequency noise reduction
  - Shot noise region: increasing the effective/detected power
- Low frequency noise reduction
  - Electronics noise that produces force noise on the test masses
  - Configuring and tuning control systems:
    - Frequency and intensity stabilization of the input beam
    - Controlling the longitudinal and orientation degrees-of-freedom of the core optics to the required levels, without introducing noise into the gravitational wave channel

Lock acquisition reliability

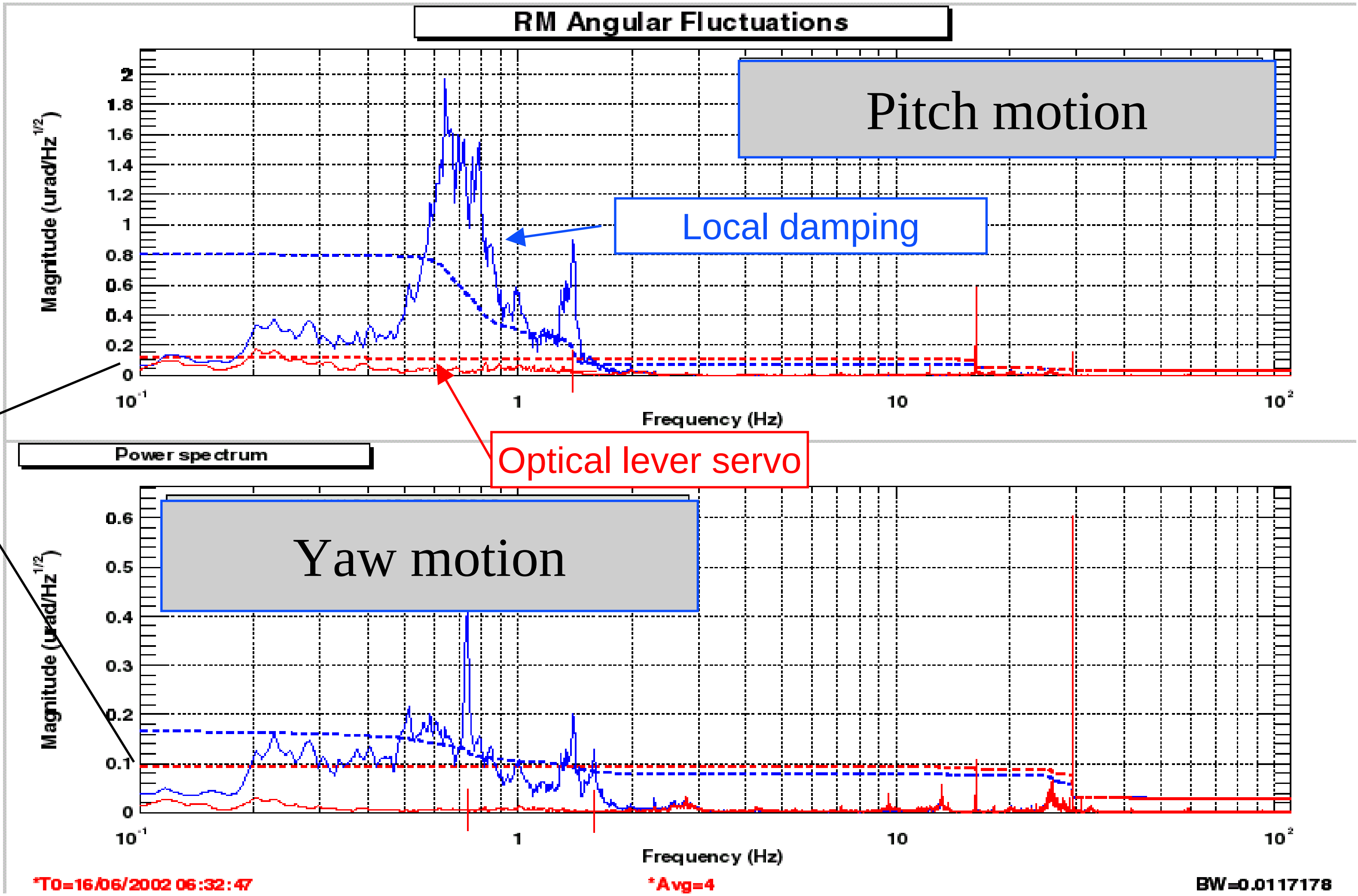
- Acquisition is not yet completely reliable (not a great hindrance either)
  - Can take ~10s, but can also be elusive for ~hours
- Initial optical alignment is a poorly controlled element in the process
  - Currently initial alignment is done manually by maximizing or minimizing power in substates of the interferometer
    - Substates: single arm cavity; simple Michelson; power recycled Michelson (unused mirrors misaligned)
  - Plan to automate the initial alignment process, using an additional wavefront sensor to provide alignment information of all degrees-of-freedom of the interferometer substates
  - Will make initial alignment more reproducible, and shorten time spent on manual alignment
  - Implementation: starting with LHO 2k, immediately after S1

Stability improvements: reduction of angular fluctuations

- Angular fluctuations of core optics lead to difficulty in locking and large power fluctuations when locked
  - Fluctuations dominated by low-frequency isolation stack and pendulum modes
  - Suspension local sensors damp the pendulum modes, but have limited ability to reduce the rms motion
- Optical lever sensors:
  - initially meant as an alignment reference and to provide long term alignment information
  - they turn out to be much more stable than the suspended optic in the ~0.5-10 Hz band
  - wrap a servo around them to the suspended optic, with resonant gain peaks at the lowest modes



Optical lever servo results



Pitch motion

Local damping

Optical lever servo

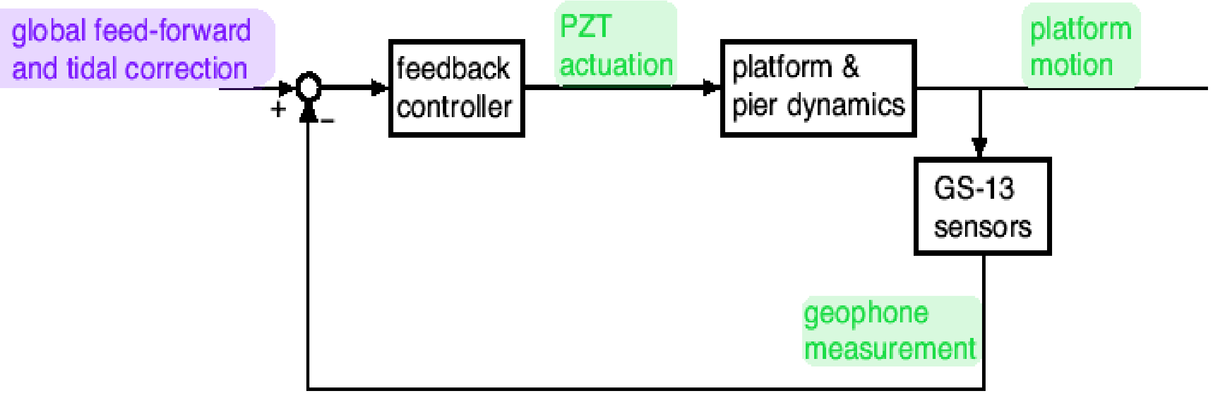
Yaw motion

10^{-7} rad

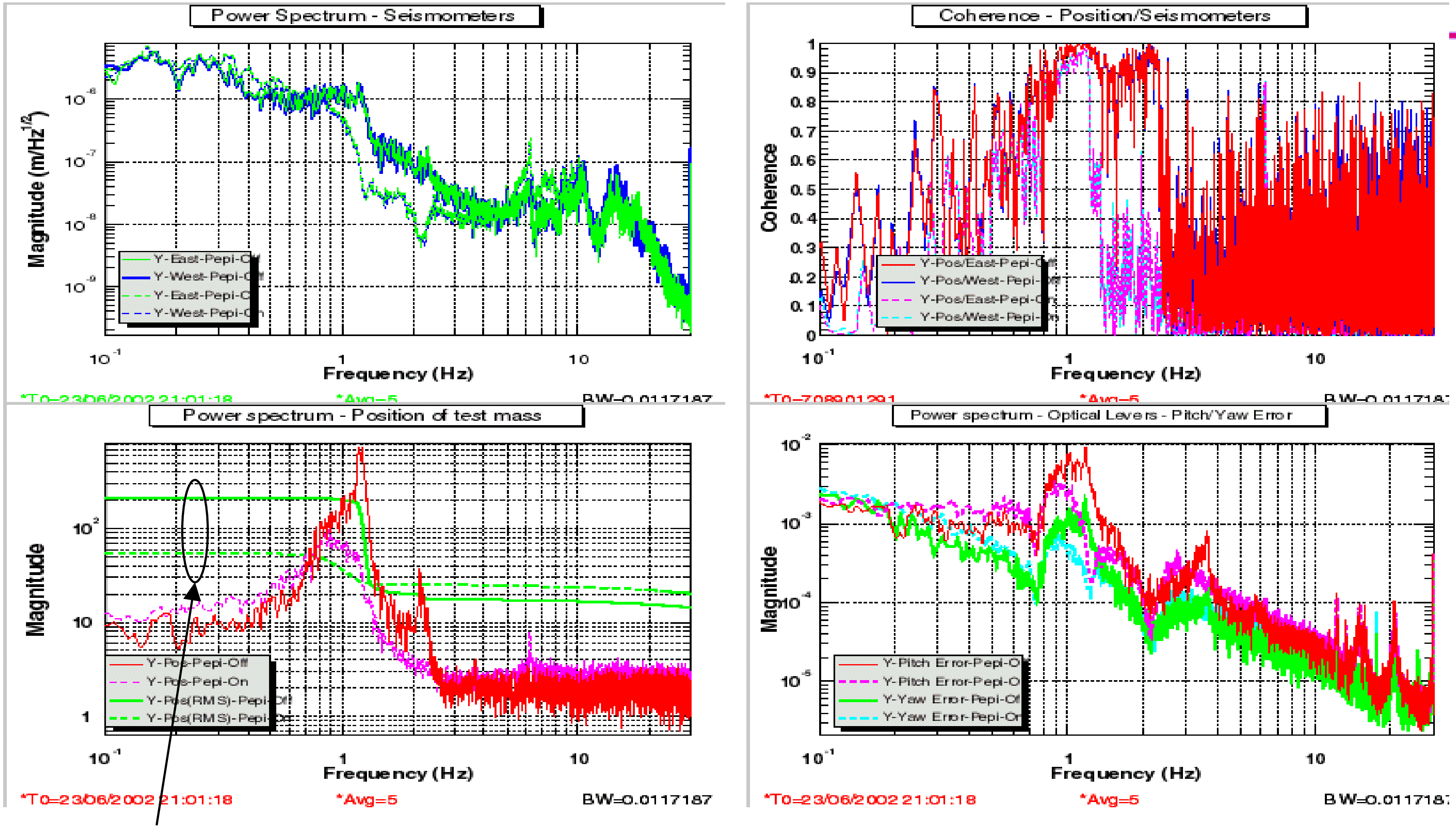
Stability improvements: seismic noise

- 2 D.O.F. external active isolation, using existing PZT fine-actuators
- Modest bandwidth, but resonant gain gives good suppression at low-f modes

SISO controller, East and West



External preisolation results: LLO End Stations
⇨ to be installed on Input Masses after S1


Power Spectrum - Seismometers

Coherence - Position/Seismometers

Power spectrum - Position of test mass

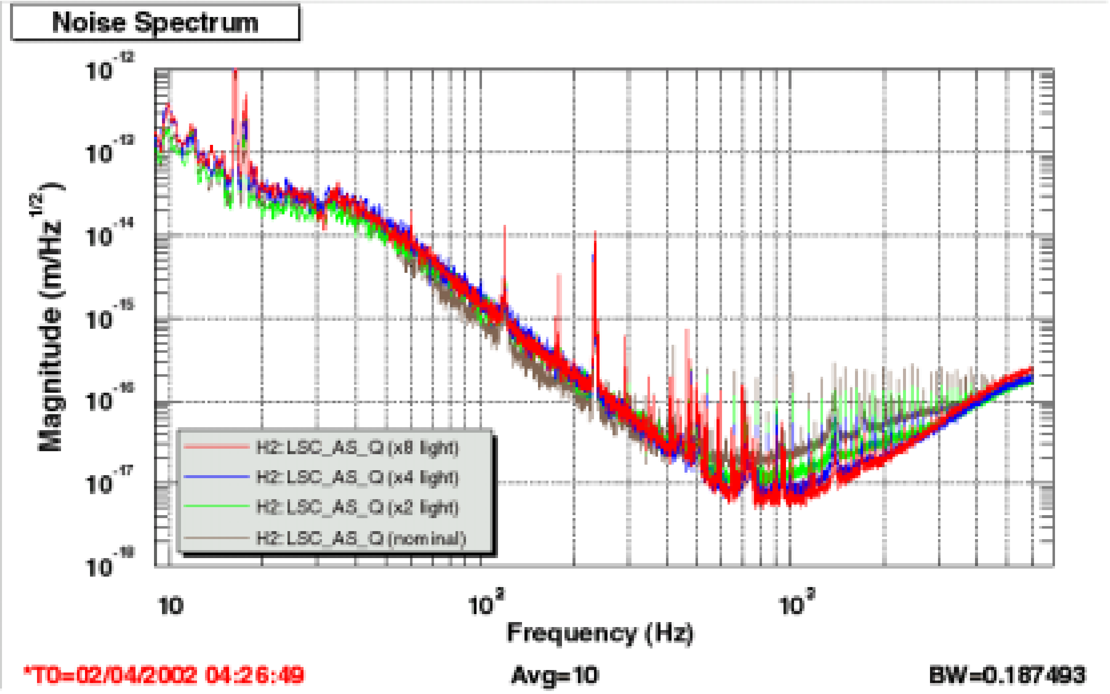
Power spectrum - Optical Levers - Pitch/Yaw Error

4x reduction in rms

High-frequency noise: shot noise

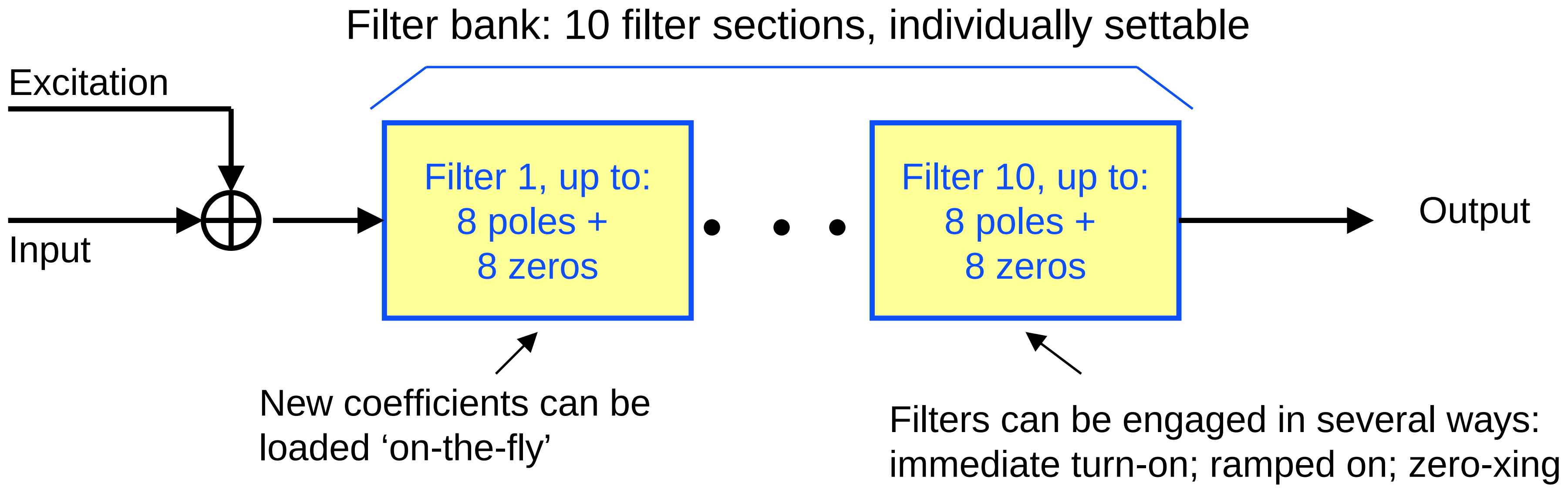
- Increasing the light on the output photodetector
  - low light level is required for lock acquisition, to avoid saturation from transients
  - light level is increased after lock using an electro-optic variable attenuator ⇒ *currently we detect about 1% of the AS port light*

- power increase limited by
  - Low-freq fluctuations of the differential mode signal
    ⇒ more low-freq gain in loop
  - Low-freq fluctuations in the orthogonal phase rf-signal
    ⇒ more suppression in other D.O.F.



Increased functionality of real-time digital filtering

- Recent real-time code enhancements have made it much easier to implement complex digital filters
  - All digital feedback systems – LSC, ASC, DSC – now use a new ‘generic filter module’



Filter bank: 10 filter sections, individually settable

New coefficients can be loaded ‘on-the-fly’

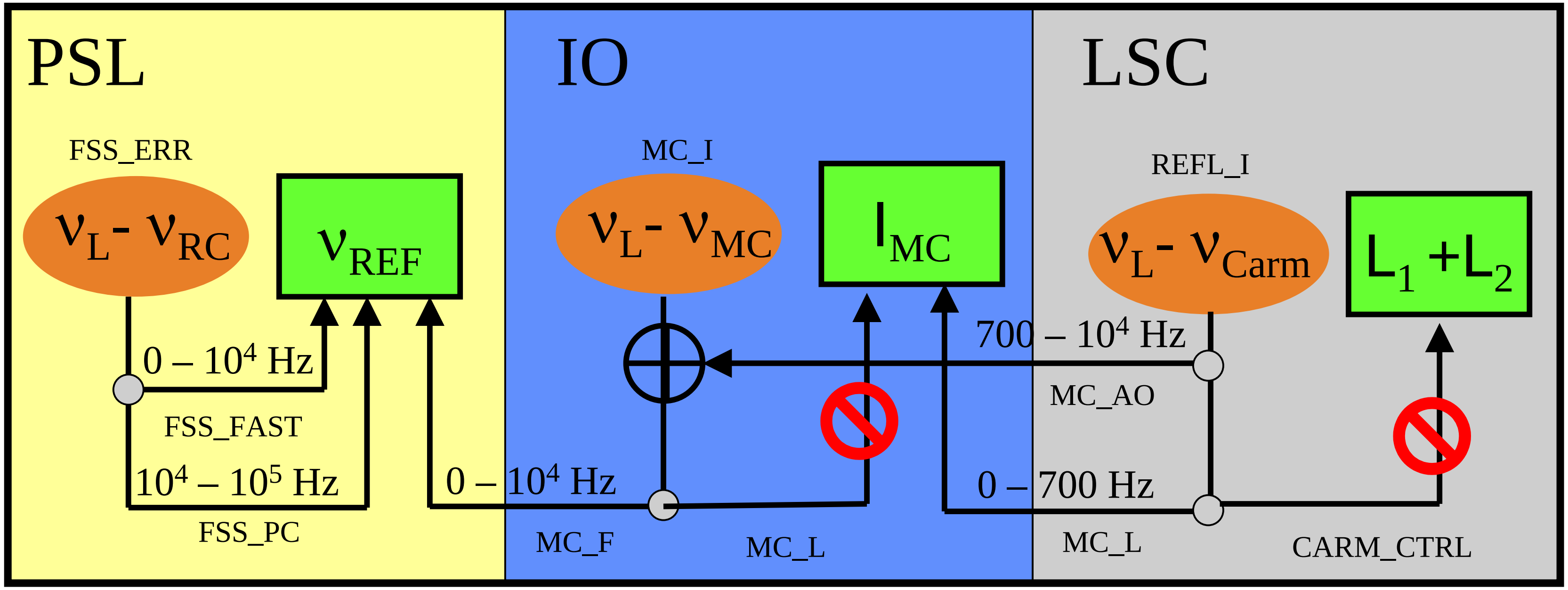
Filters can be engaged in several ways: immediate turn-on; ramped on; zero-xing

- Incremental improvements on processing & I/O time have also helped

Low frequency noise: common mode servo

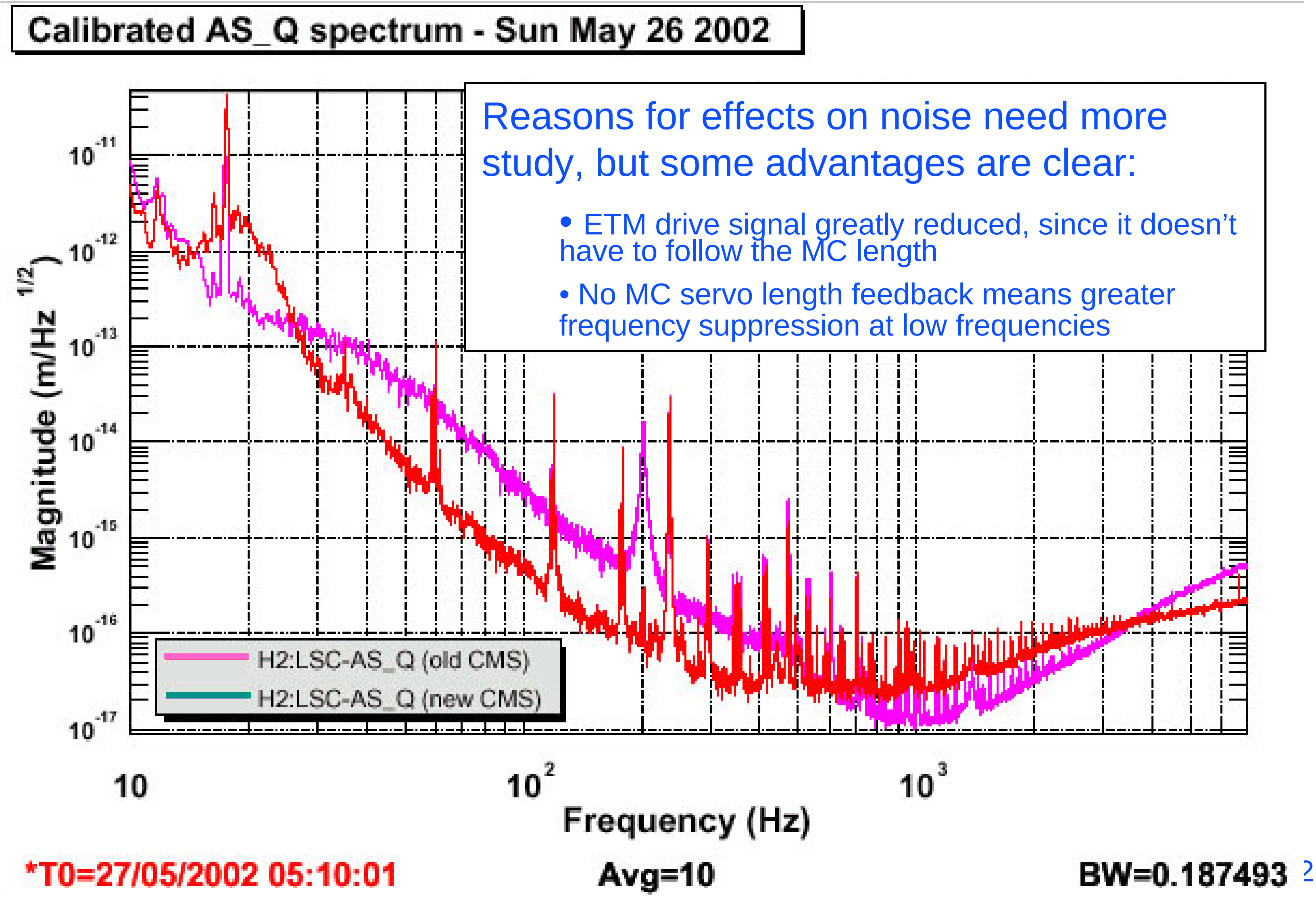
- What is it? Feedback loop from the 'common mode' error signal – error between the average arm length and the laser frequency – to the laser frequency
  - Provides the final level of frequency stabilization, after the prestabilization and mode cleaner stages
  - Ultimately, need a stability of 3×10^{-7} Hz/rtHz at 150 Hz
  - Lock is acquired with feedback only to the end mirrors …
  - the tricky operation is then to transfer the common mode feedback signal to the laser frequency, with multiple feedback paths
- Status
  - LHO 2k: operational in final configuration, not fully characterized
  - LLO: operational in an older, now obsolete configuration
  - LHO 4k: not yet operational
  - Noise impact: LHO 2k & LLO display no coherence between common and differential channels
    - Linear coupling is not a current limit
    - Doesn't rule out some non-linear coupling
  - Frequency coupling measured on LHO 2k: 300:1 rejection ratio! (100 Hz)

Frequency stabilization feedback configuration



- Recent innovation: once locked, eliminate length feedback to the end masses (CARM_CTRL) and to the mode cleaner (from the MC error signal)
  - MC length feedback still needed for acquisition, otherwise length fluctuations are essentially multiplied up by the arm:MC length ration, but once locked …
  - MC frequency is slaved to that of the long arms at all frequencies below ~500 Hz

Effect of feedback change on differential mode noise



Reasons for effects on noise need more study, but some advantages are clear:

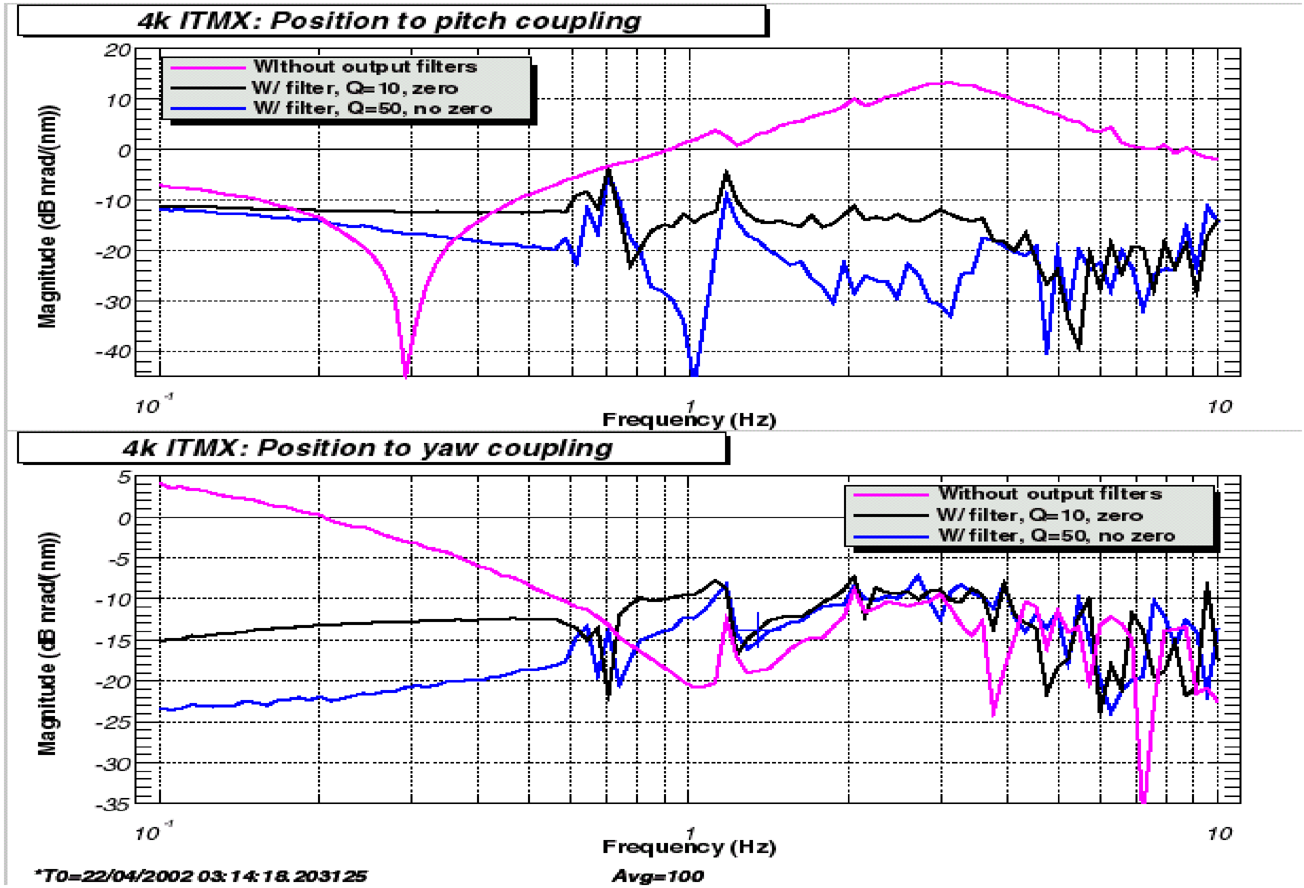
- ETM drive signal greatly reduced, since it doesn't have to follow the MC length
- No MC servo length feedback means greater frequency suppression at low frequencies

LHO 4k: Development ground for new suspension controls (DSC)

- **Why a new suspension controls system?**
  - Coil driver design limitation:
    - Relatively large coil currents needed for mirror dc alignment and lock acquisition, but small currents to hold lock
    - Coil driver design made it impractical to reduce longitudinal control range after lock ⇨ couldn’t achieve the noise benefits of a smaller range
  - Local sensing & damping electronics, and coil drivers (including LSC & ASC input conditioning) made all on one board
    - Made changes very difficult to implement; more modularity desired
- **Moved to a system with a digital processing core & more modular analog components**
  - Much easier to implement & change digital filtering; low freq filters don’t require big C’s
  - Suspension signals digitally integrated with LSC/ASC
  - Alignment bias currents are generated and fed in independently of the feedback signals

Example of filtering benefit with DSC

- Force-to-pitch coupling inherent in suspension
  - Feedback forces produce pitch misalignment
  - Previously, could balance torques at one frequency: DC most important



- with DSC, easy to implement a frequency-dependent compensation that balances torque at all frequencies

Low frequency noise: dealing with DAC noise

- Dynamic range of test mass control signals exceeds that of the DAC:
  - (DC force/GW band acceleration x mass) = 3×10^9 rtHz
  - 16-bit DAC (peak voltage/noise voltage) = 3×10^5 rtHz
- Range mismatch accommodated with a post-DAC analog ‘dewhitening filter’
  - Essentially a (very sharp) low-pass filter, to attenuate DAC noise in the GW band, where very little control range is needed
  - Currently 40-55 dB attenuation is achieved for f > 100 Hz, of which 30-40 dB is needed
  - Engaging the dewhitening filters
    - filters must be removed for lock acquisition: need full actuation range for ~100 Hz signals
    - Engaging while in lock is tricky: switching transients can throw it out
    - Ongoing effort to minimize the switching transients
- Lower noise DACs: Frequency Devices is developing for LIGO a VME DAC module with ~100x lower noise

Summary

- What has been done
  - Significant noise improvements on LHO 2 & LLO over last 6 mths
  - LHO 4k locking reasonably reliably
  - Digital Suspension systems implemented
  - Stability improvements: optical lever stabilization, external preisolation
  - Many improvements in electronics/software/training
    - Site operators playing a much bigger role in day-to-day running of interferometers
- Some plans for near-term (only 4 mths between S1 & S2)
  - Improved common mode servo on remaining 2 ifos
  - Two more 2 D.O.F. preisolators for LLO
  - Full wavefront sensor alignment control
  - Digital suspension systems on remaining 2 ifos
  - Continue automating procedures