The commissioning of the VIRGO central interferometer

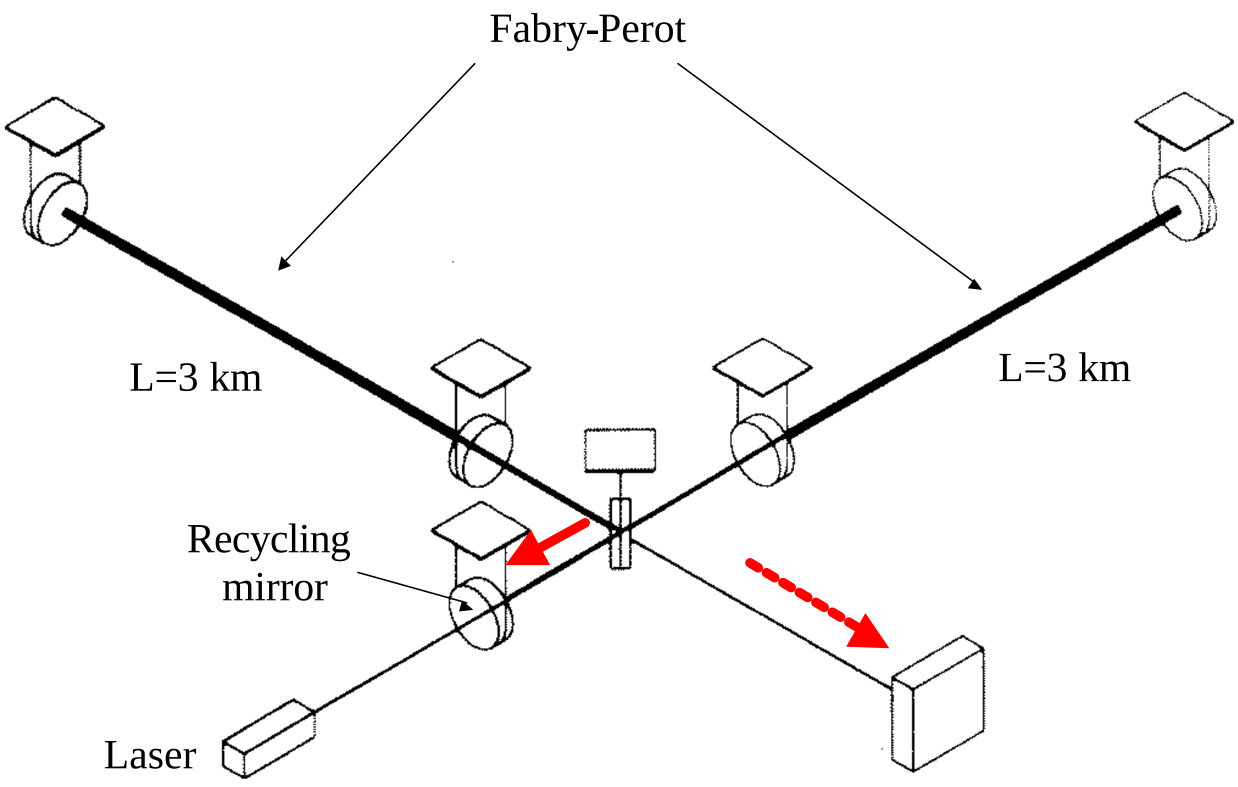
for the Virgo Collaboration

Raffaele Flaminio

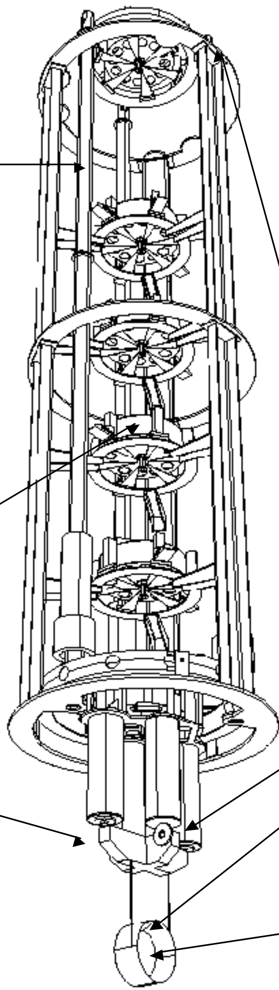
L.A.P.P. - IN2P3

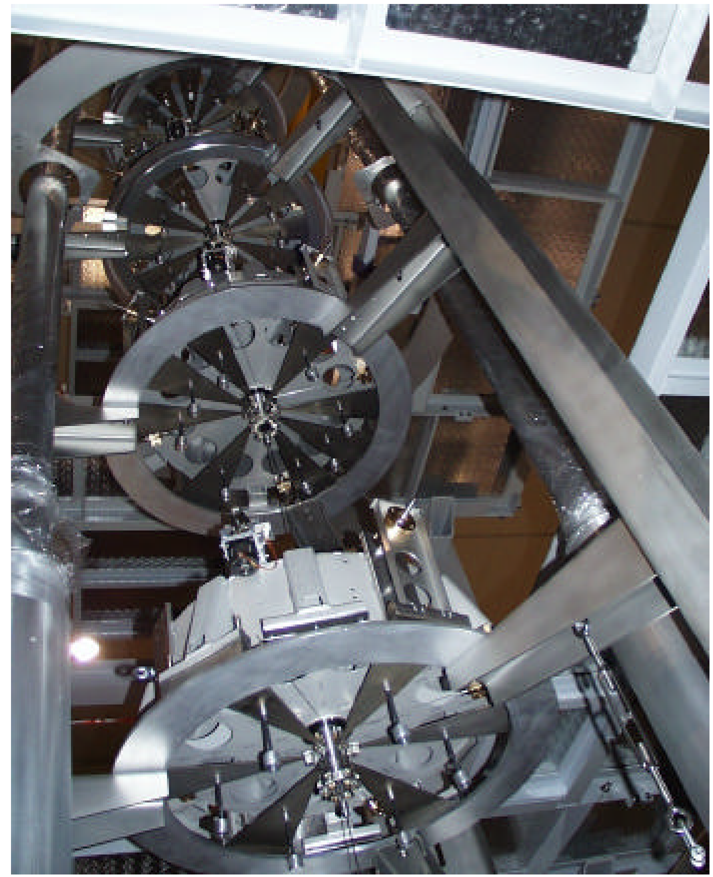
The VIRGO detector

- Arms 3 km long
- Fabry-Perot cavities
- Dark fringe
- Power recycling
- Large mirrors
  - fused silica
  - low losses
  - low scattering



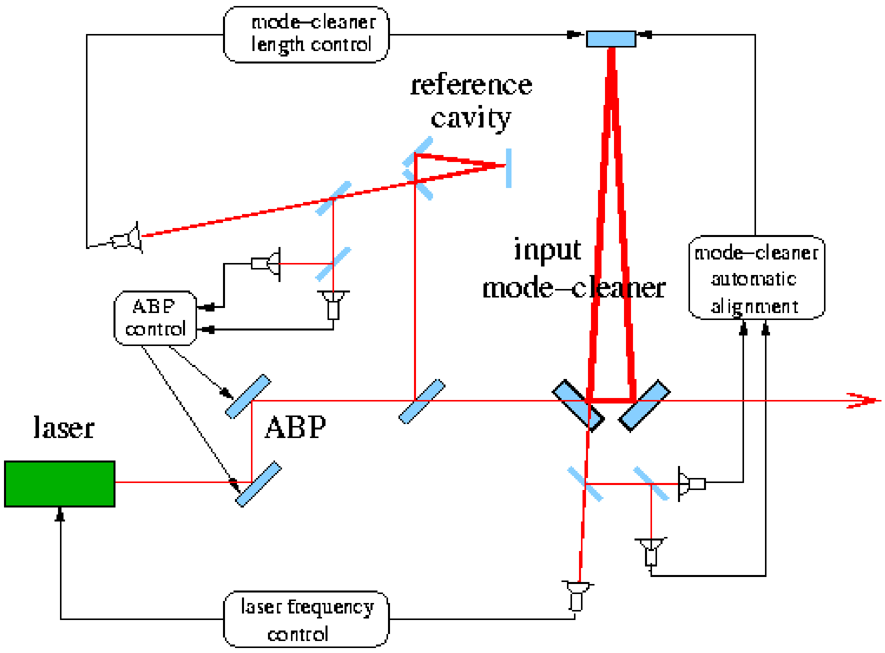
Mirrors suspensions

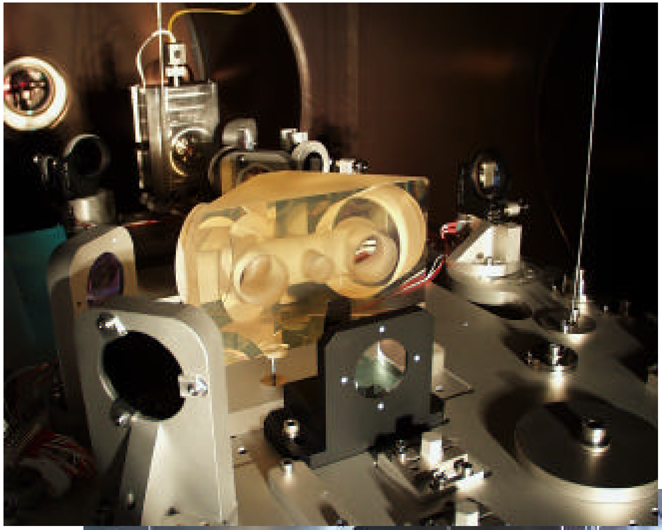


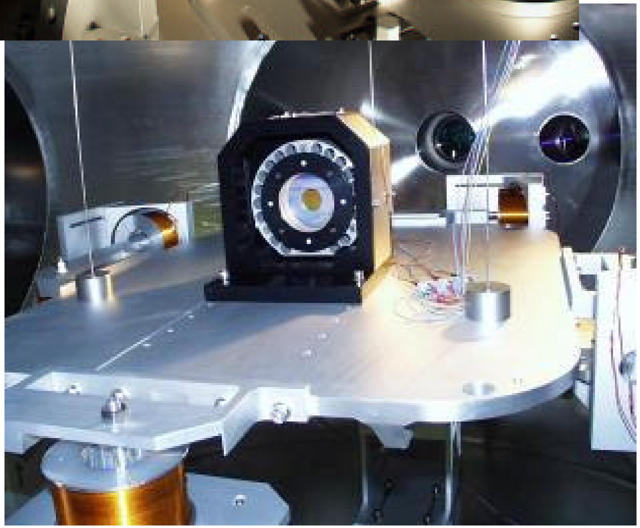


Injection system

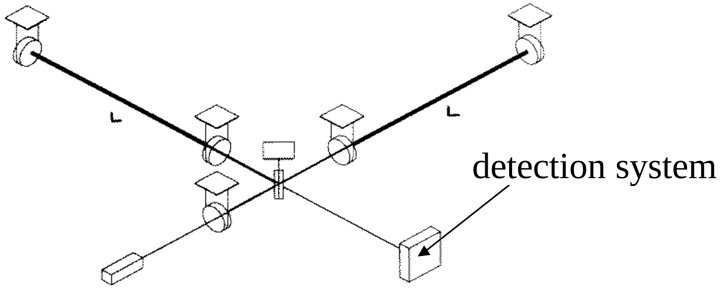
- Light source: 20 Watts Nd:YAG laser
- Laser frequency and power stabilizations
- ULE high finesse cavity for frequency reference
- 150 m long mode-cleaner for beam jitter filtering



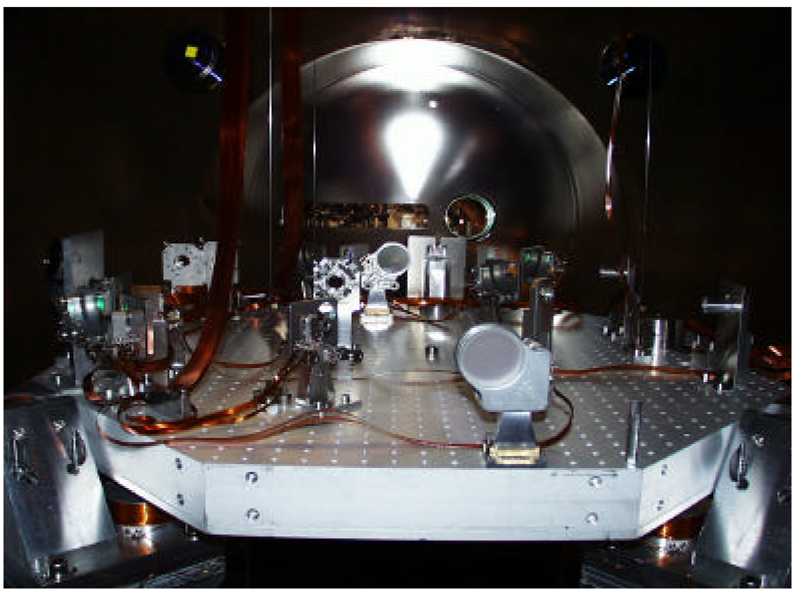


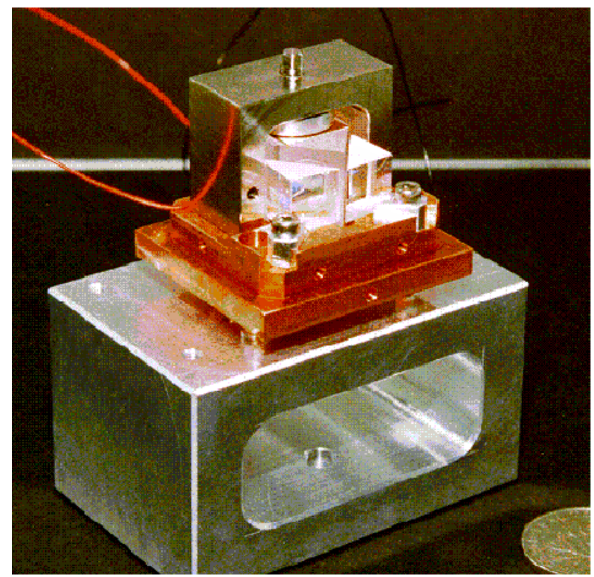


Detection system



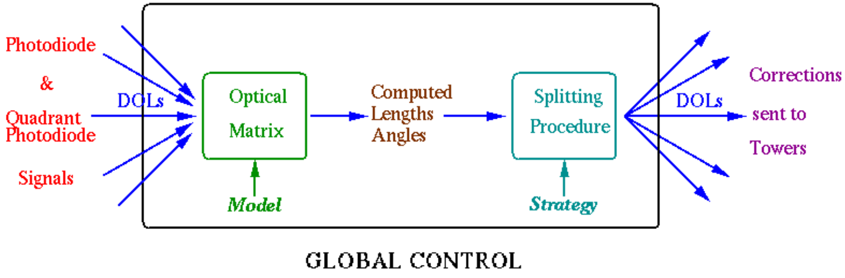
- Output telescope
- 4 cm long output mode-cleaner for beam filtering
- High quantum efficiency InAsGa photodiodes
- Signal amplification & synchronous detection

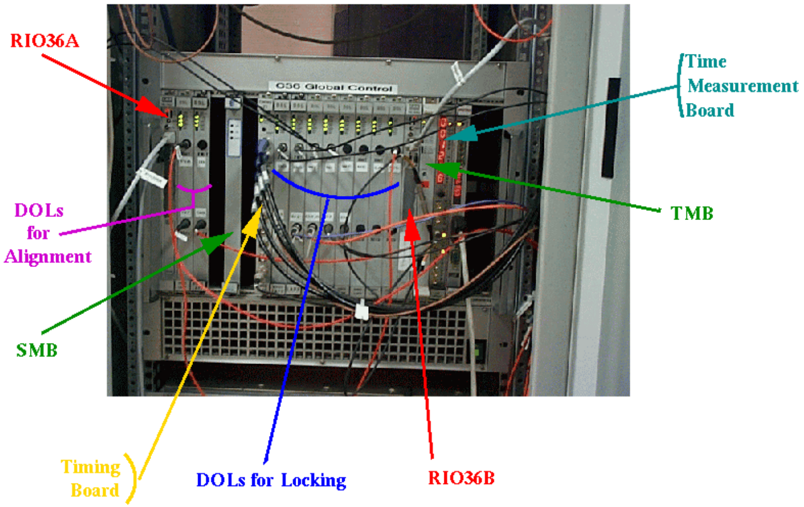




Interferometer control system

- Photodiode signals digitized at 20 kHz with 16 bits ADC
- Signals sent at 10 kHz to Global control through digital optical link (DOL)
- Correction signals calculated in global control in 100 µs
- Correction signals sent to Suspension control crates via DOL
- Correction signal applied to coil via 20 bits DAC



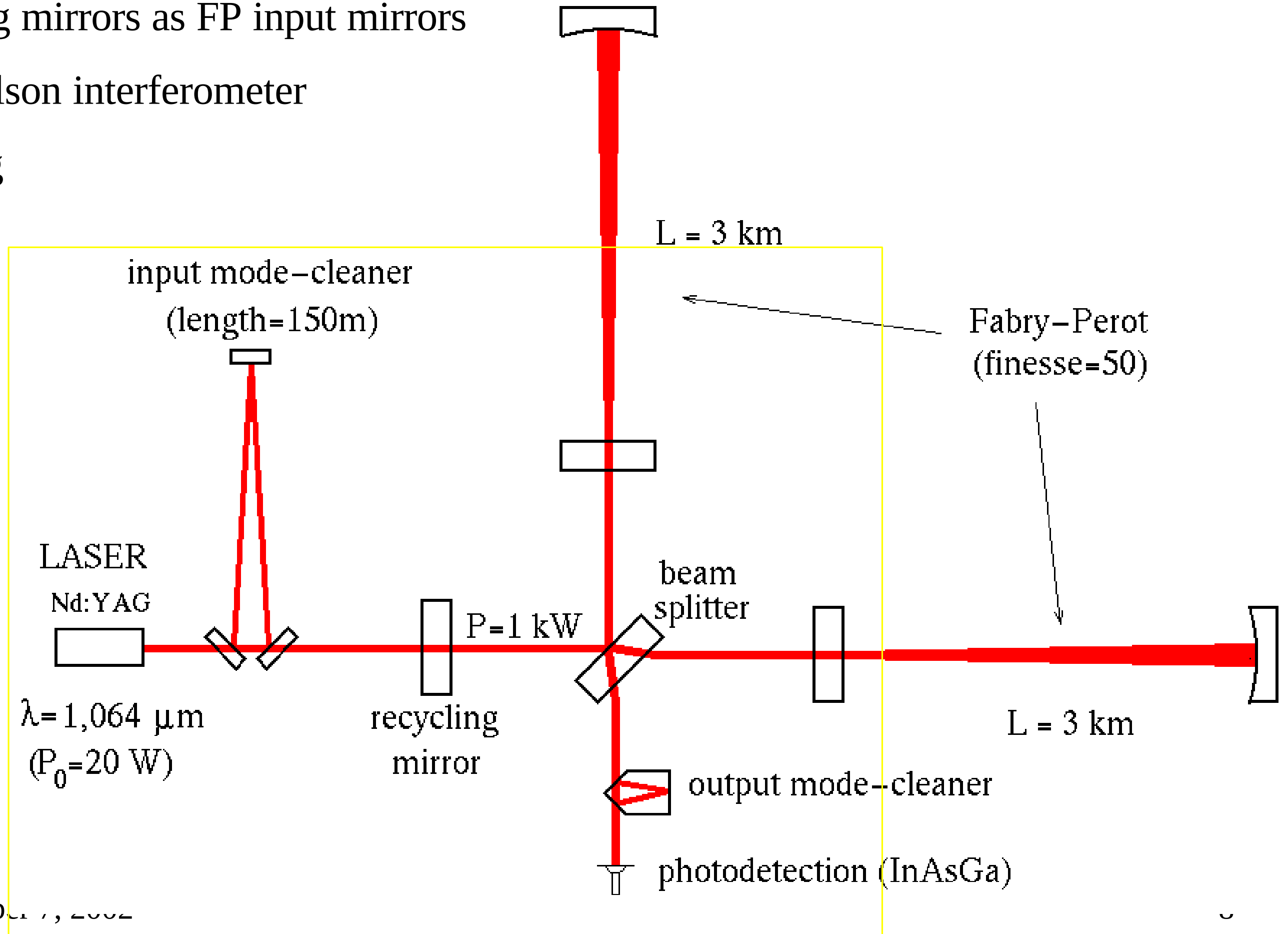


Construction of VIRGO

- 3 km arms and all buildings completed last winter
- Central area available since 1998

The central interferometer (CITF)

- Totally reflecting mirrors as FP input mirrors
- Recycled Michelson interferometer
- Arms ~ 6 m long



CITF vs Virgo

- Central interferometer: first full test of the Virgo design
  - *same* suspensions
  - *same* light injection system
  - *same* light detection system
  - *same* interferometer control system
  - *same* environmental monitoring
  - *same* DAQ

- Main differences
  - no Fabry-Perot cavities !
  - smaller beam size (different input/output matching optics)
  - slightly different modulation frequency
  - no pre-mode-cleaner (there will be one in Virgo)
  - 10 W laser (it will be a 20 W laser in Virgo)
  - smaller mirrors (attached to holders with final mirrors size)

Goals of CITF commissioning

Goals

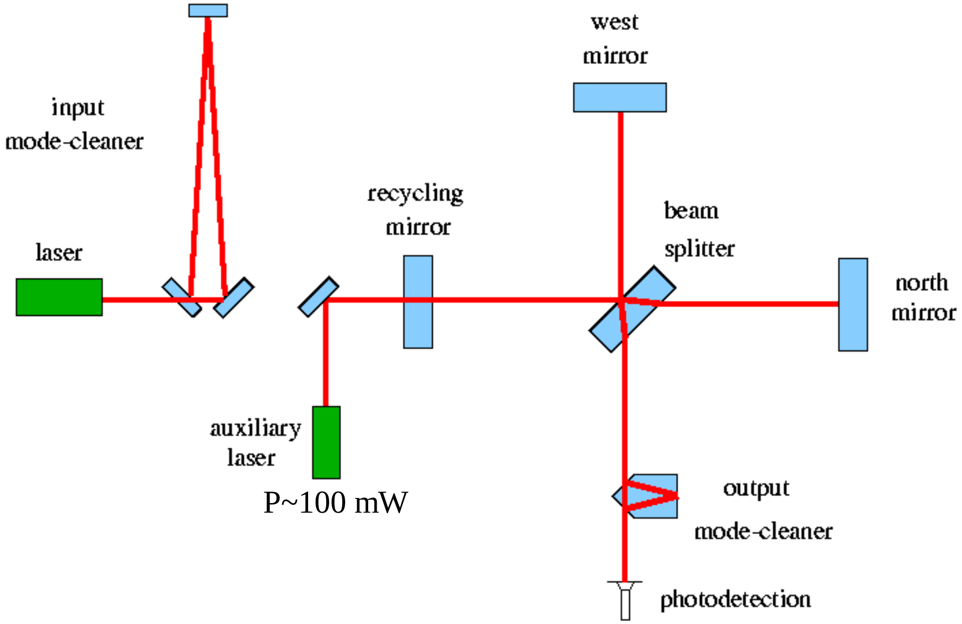
- Verify technical choices made for VIRGO
- Learn and train people to run a suspended interferometer
- Start to study the effect of technical noise on data analysis

Tasks

- Set-up the interferometer control system
- Study the interferometer control reliability
- Study the interferometer sensitivity

CITF main steps

- Vacuum chamber installation in 1999
- Interferometer installation in 1999 and 2000
- Suspensions pre-commissioning in 2000
- Injection system pre-commissioning longer than originally thought
- CITF Commissioning started with small auxiliary laser in February 2001

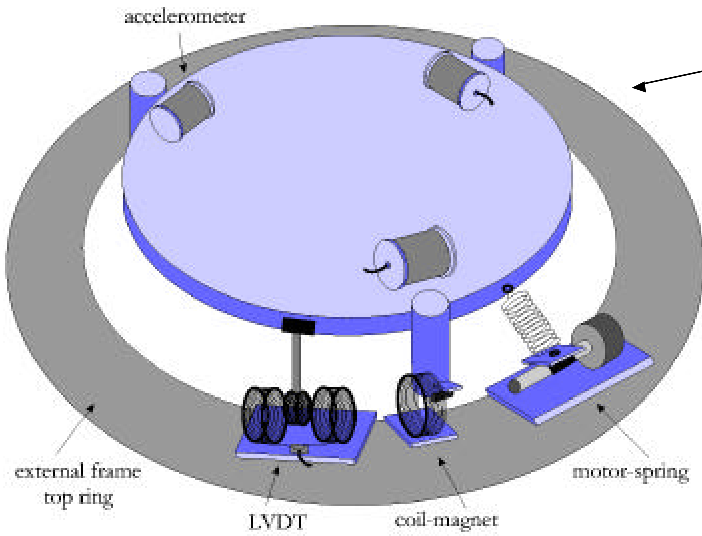


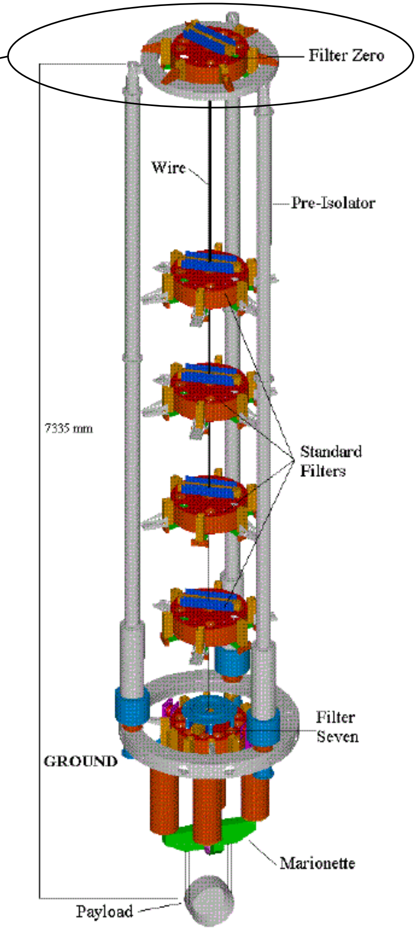
Main CITF commissioning steps

- Interferometer first alignment
- Simple Michelson
- Recycled Michelson
- Recycled Michelson with Injection

Inertial damping

- Goal: damp suspension internal resonance's

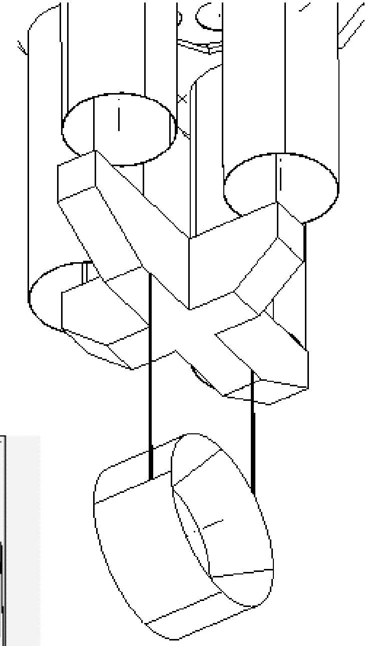




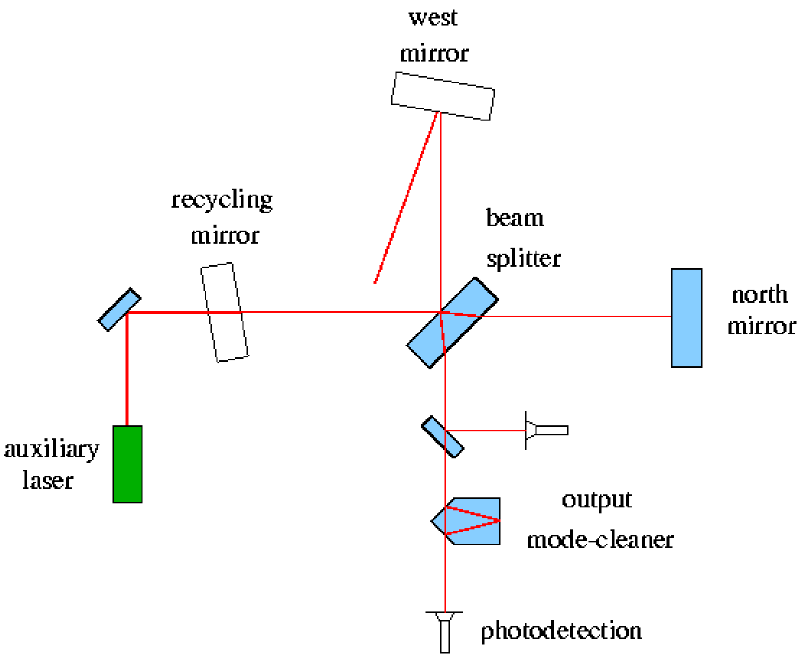
- Accelerometers sense top stage motion respect to an inertial frame
- Use LVDT's to sense top stage motion respect to ground
- Feedback to top stage using electro-magnetic actuators

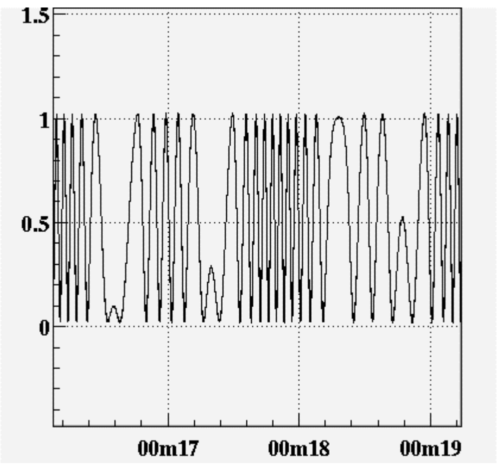
- Mirror motion reduced to 1 μm above 30 mHz

Local control



- Mirror alignment respect to ground
  - readout based on optical lever + CCD camera (10^{-7} rad/√Hz)
  - digital control
  - actuation through coils acting on ‘marionetta’
  - mirror alignment controlled with a bandwidth of 200 mHz
  - residual motion < 1 μrad (rms)





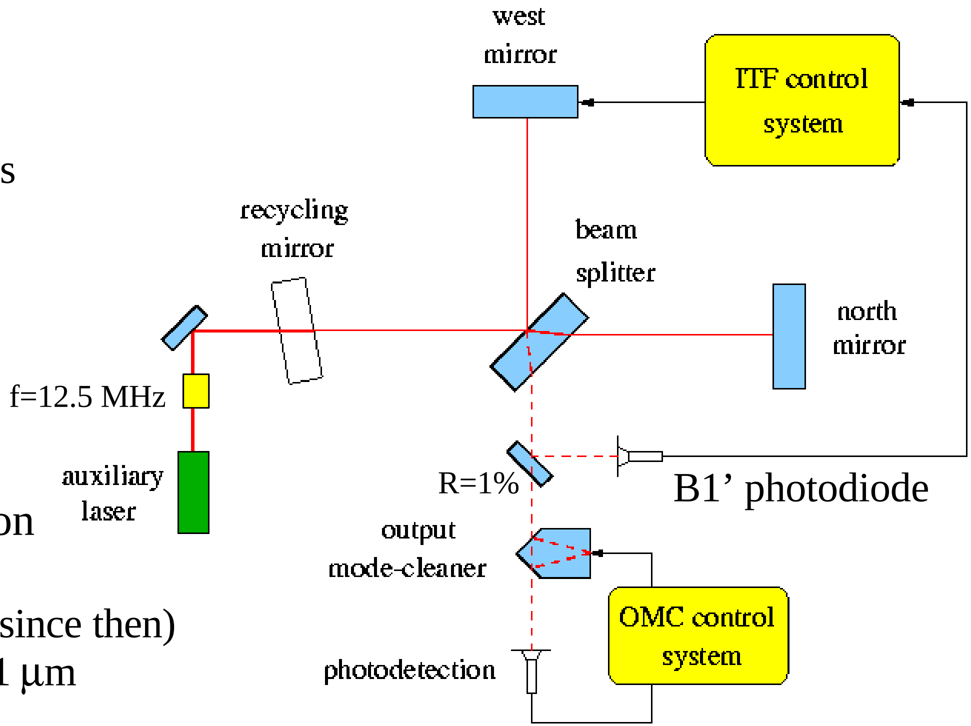
May 2001: first fringes

Simple Michelson: locking

- Simple strategy:
  - error signal from photodiode B1'
  - feedback to west mirror recoil mass

- Feedback characteristics:
  - bandwidth ~ 15 Hz - 30 Hz
  - locking accuracy ~ 1 nm
  (improved since then)

- First measurements of mirrors motion
  - most of the motion below 50 mHz
  - amplitude ~ 10 µm p-p (improved since then)
  - mirrors motion above 100 mHz < 1 µm

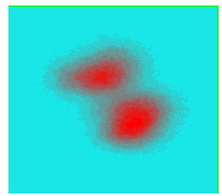


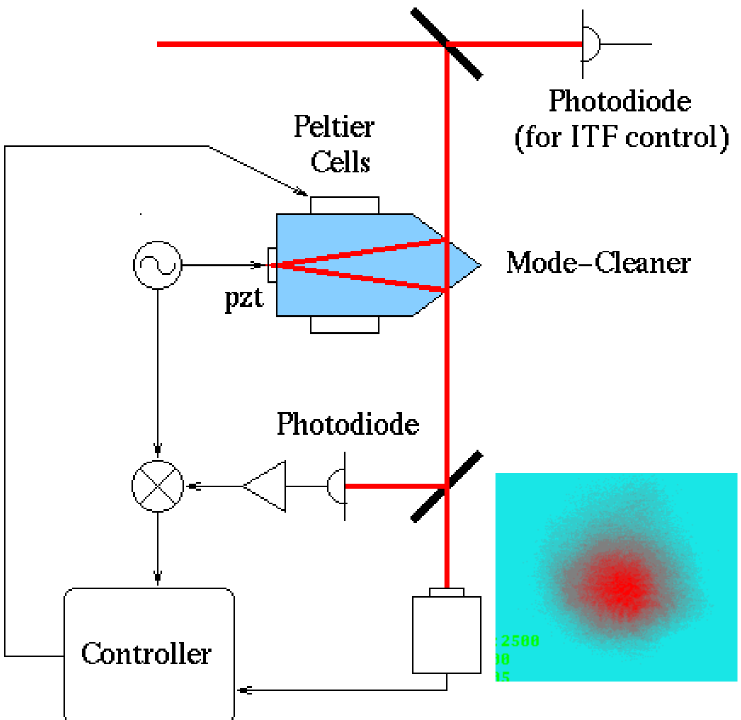
- Low frequency correction sent to suspension top-stage

Easy to control super-attenuator mirrors with small bandwidth feedback !

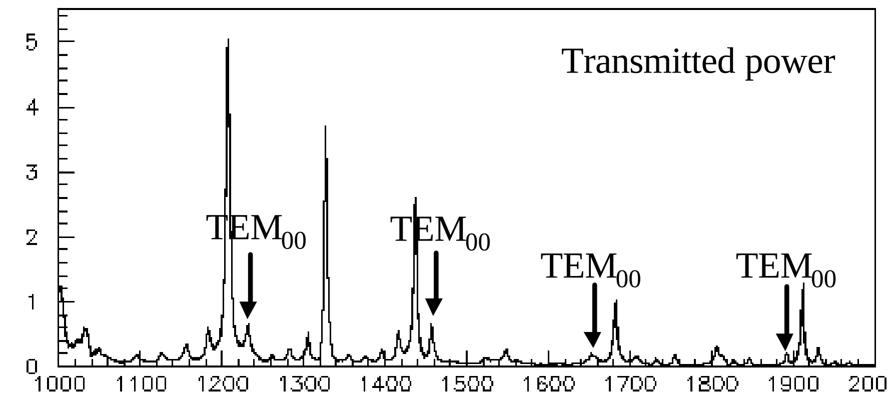
Output mode-cleaner locking

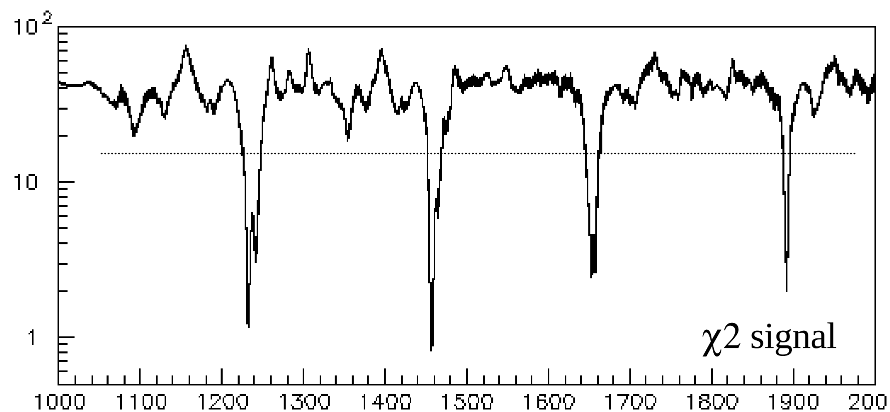
contrast ~ 1 %





contrast ~ 0.1%

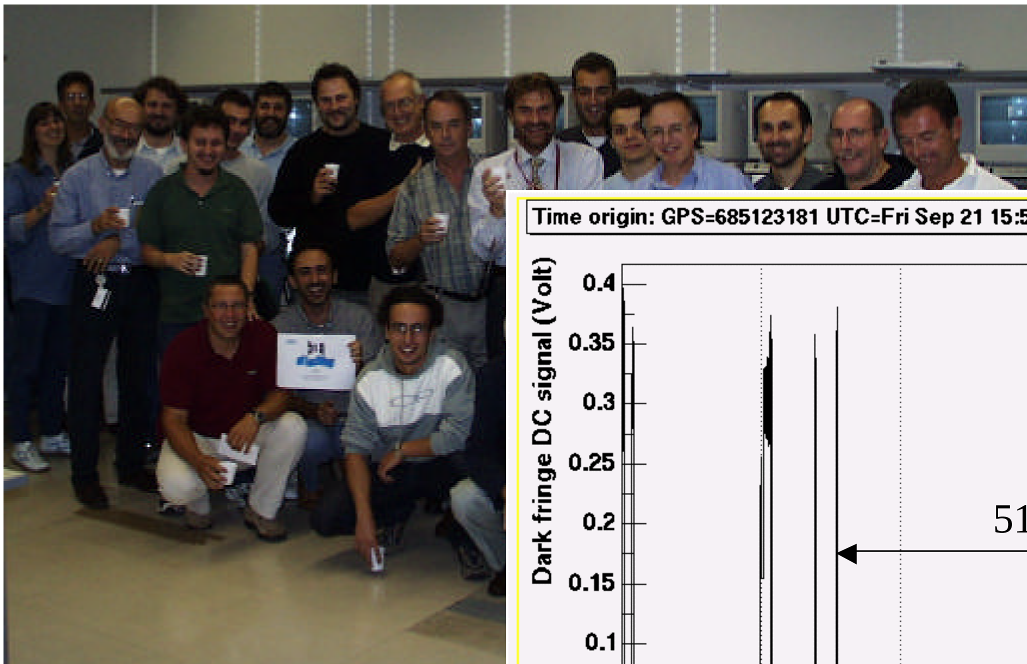


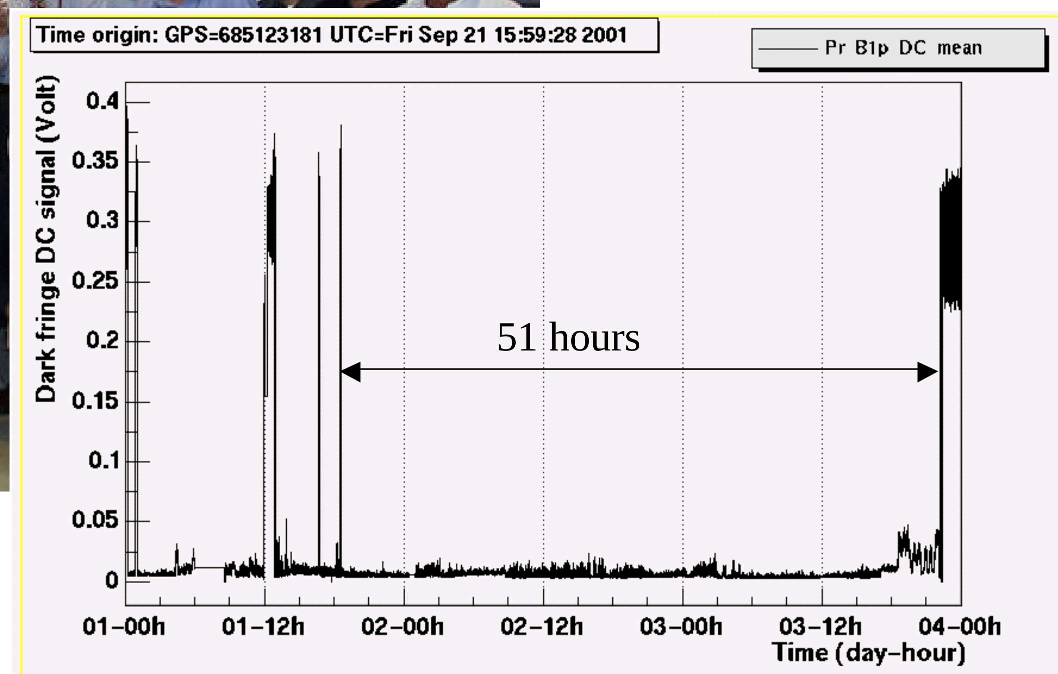


Simple Michelson long term test

• Control robustness tested during first engineering runs (ITF run for 3 days 24h/24h)
  - E0: Sep. 2001, E1 Dec. 2001

ITF continuously locked on dark fringe for more than 50h





Simple Michelson sensitivity

- Readout noise above 30 Hz (100 nW on the photodiode)

- Sensitivity below 30 Hz limited by down conversion of high frequency noise

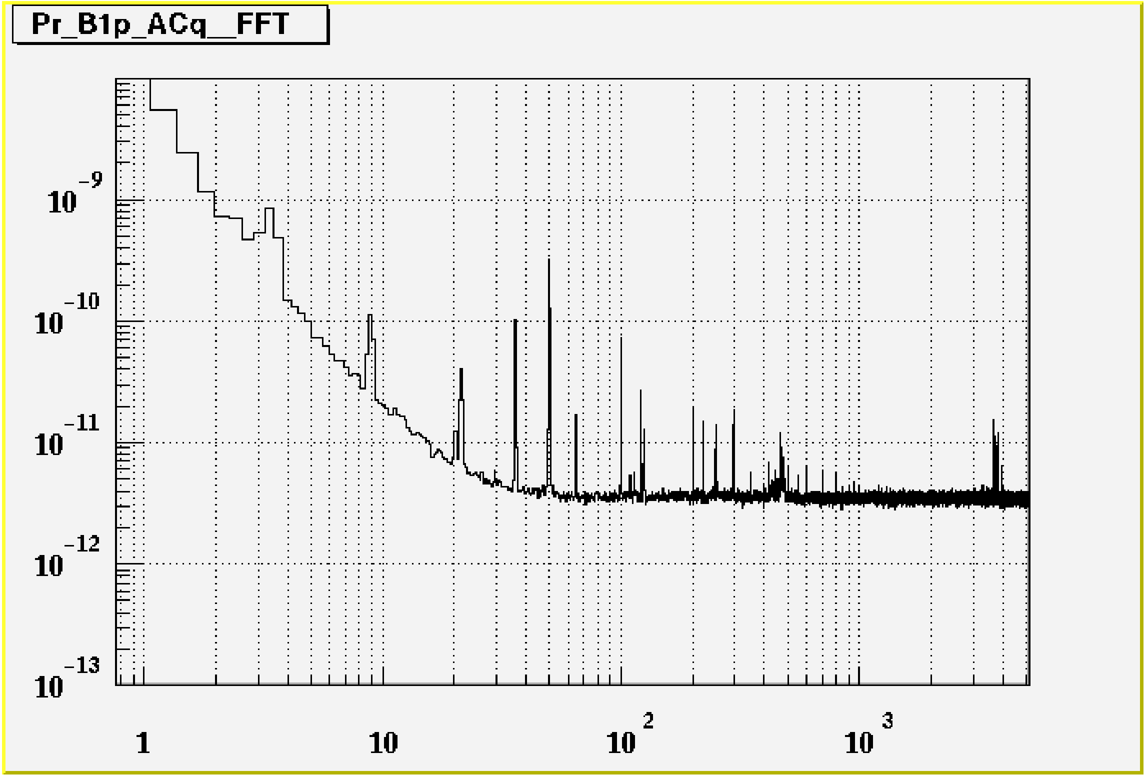
- Down conversion due
to non-linearity

- Non linearity in the actuator

- Due to Foucault currents
in the mirror holder (Al)

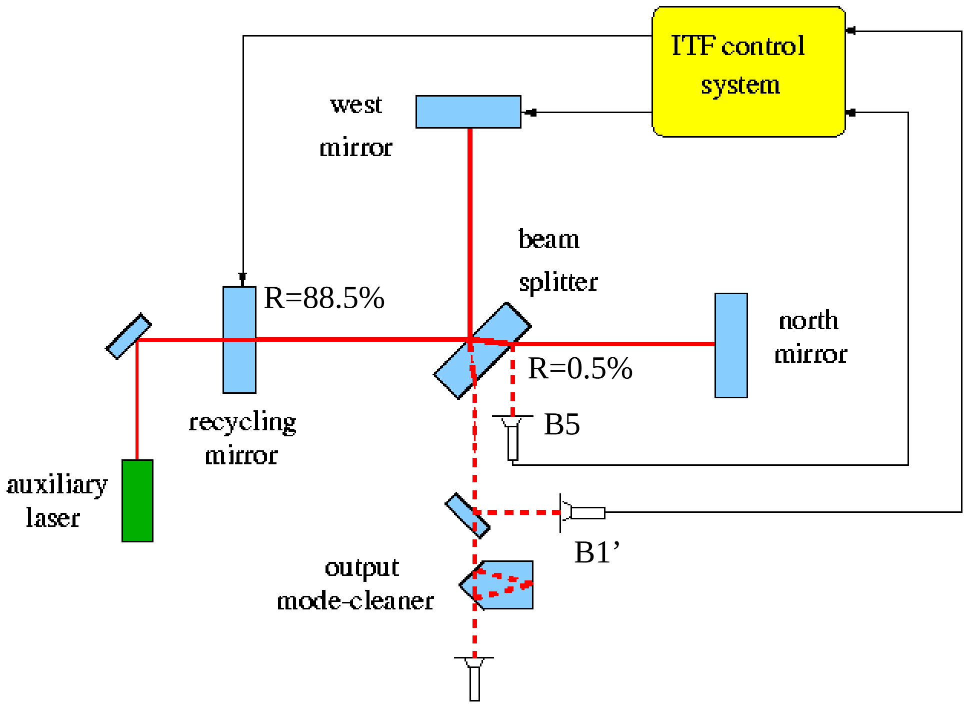
- Simulation confirmed the
-model

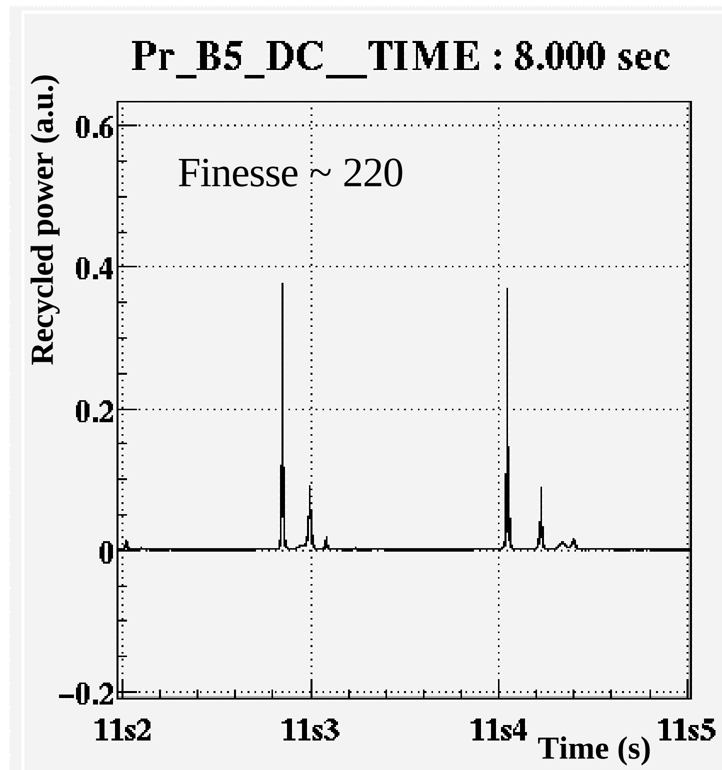
- Problem will disappear
in Virgo (no mirror holder)



Recycled Michelson operation

- Locking strategy:
  - dark fringe signal (B1’) to West mirror
  - pick off signal (B5) to Recycling mirror
- Cavity crosses resonance in short time if pendulum motion gets excited
- Lock acquisition issues

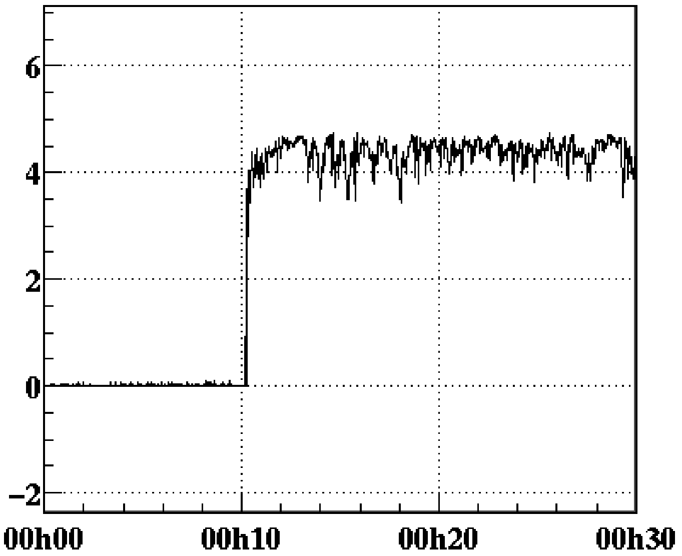




Recycled Michelson lock acquisition

1) Mirrors damping performed using interferometer signal
   - speed reduced to < 1μm/s
2) Trigger on recycling power
   - smaller risk of pendulum motion excitation
3) Use of linearized signal (AC/$DC^{1.5}$)
   - increase of signal linear range

Recycling cavity power (a.u.)



First CITF lock (Dec. 01) acting on mirrors
- control robust (8 h the first time)
- recycling factor ~100
- locking accuracy ~ 10 pm
(improved to 1 pm since then)

Sensitivity limited by aux laser frequency noise

Laser frequency stabilization

- Sensitivity limited by laser frequency noise over a large part of the spectrum

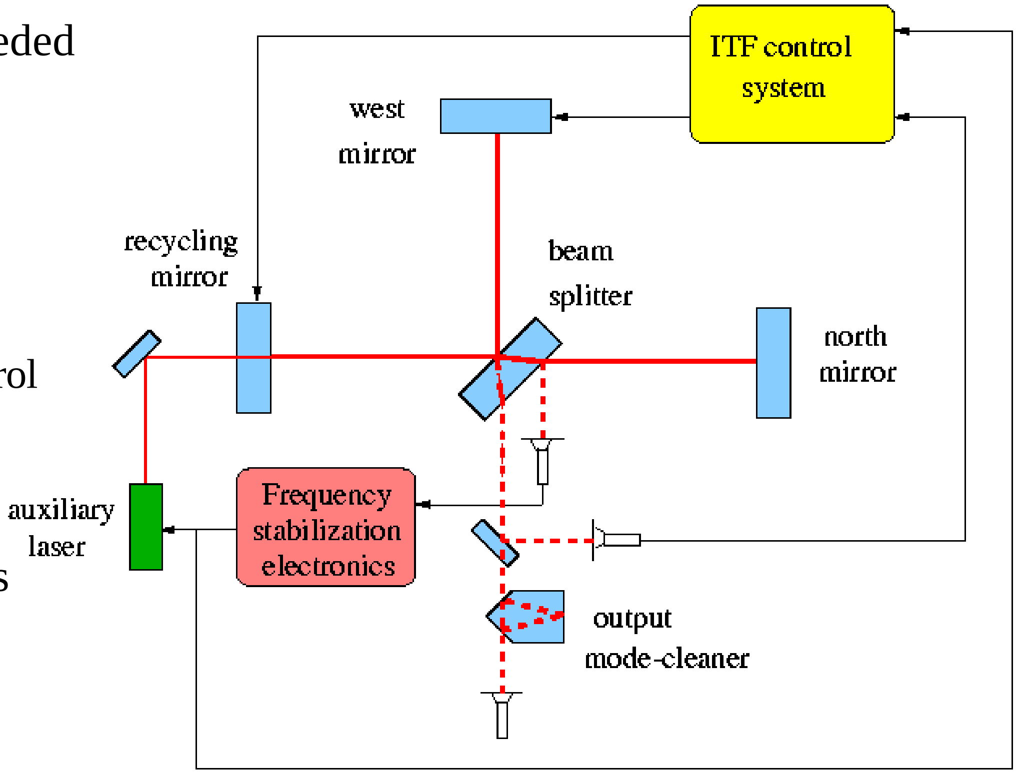
- Laser frequency stabilization needed

- Double loop on common mode:

1) pick off signal used to control laser frequency up to 10 kHz (analog feedback)

2) laser correction signal used to control recycling mirror below 3 Hz (digital feedback)

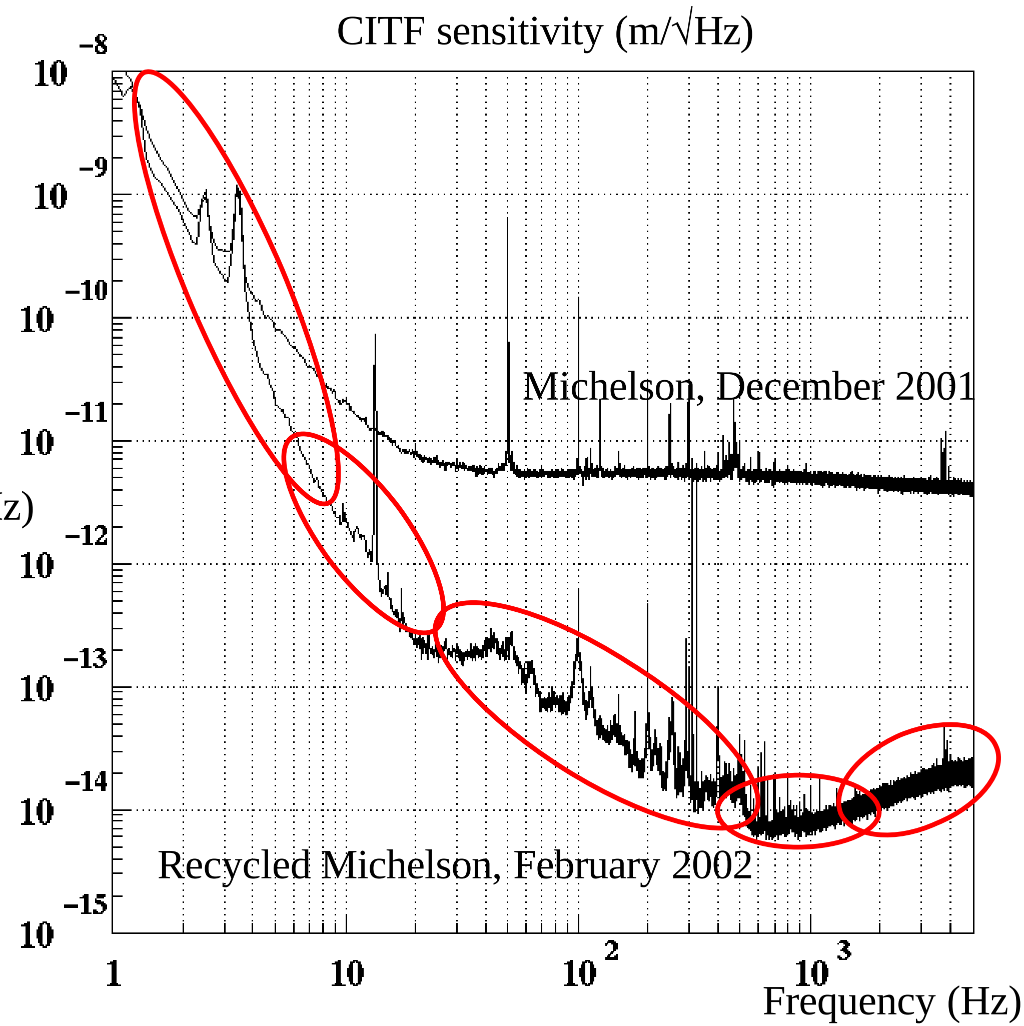
- Laser frequency noise disappears between 20 Hz and 2 kHz



Recycled Michelson sensitivity

February 2002

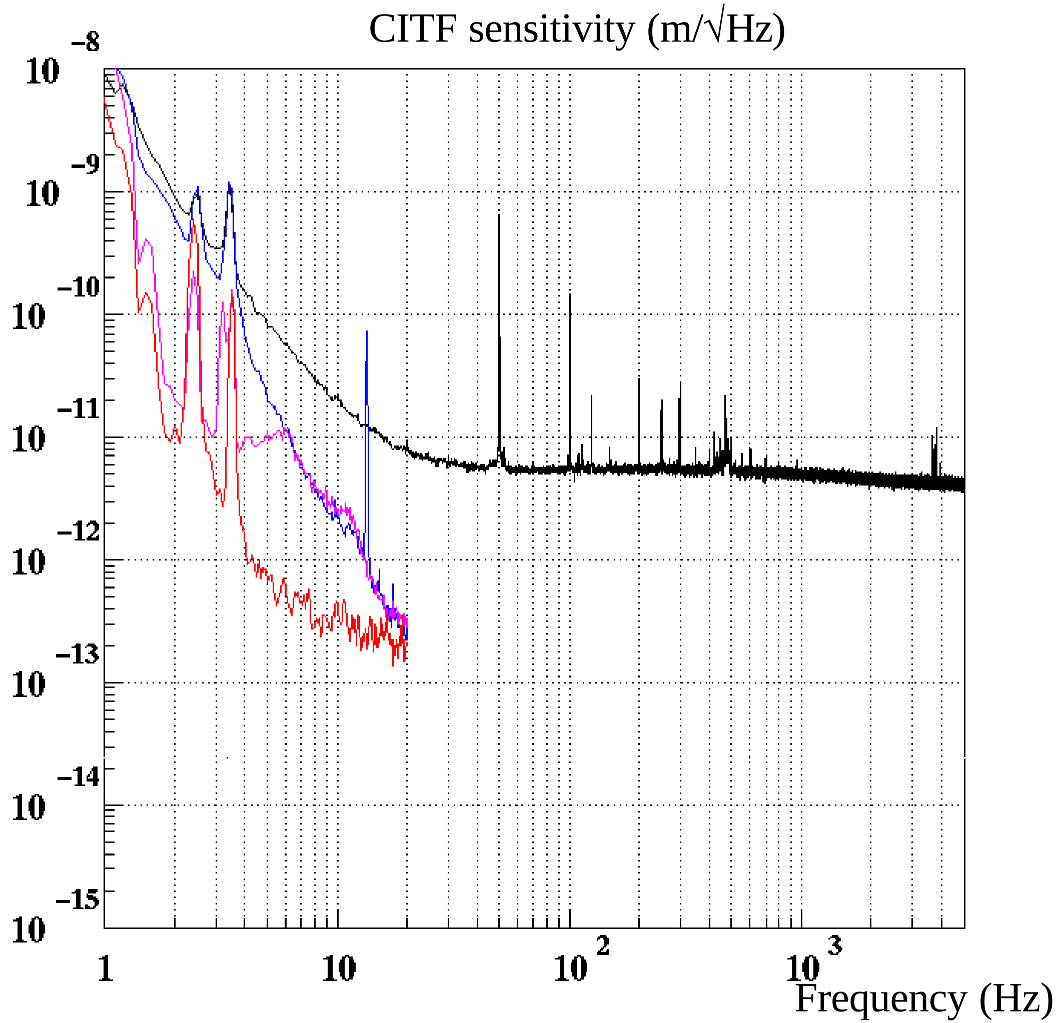
- Main sources of noise
  - local control noise (< 10 Hz)
  - laser frequency noise (~ 10 Hz)
  - environmental driven noise (20-600 Hz)
    - 'jitter' noise ?
    - diffused light noise ?
  - electronics noise (600-1000 Hz)
  - laser frequency noise (> 1000 Hz)



Sensitivity studies: below 10 Hz

March-April 2002

- Blue: February sensitivity
- Pink: Local control improved
- Red: Common mode signal used to stabilize laser at all frequencies (no double loop)



Sensitivity studies: above 600 Hz

- Limit given by:

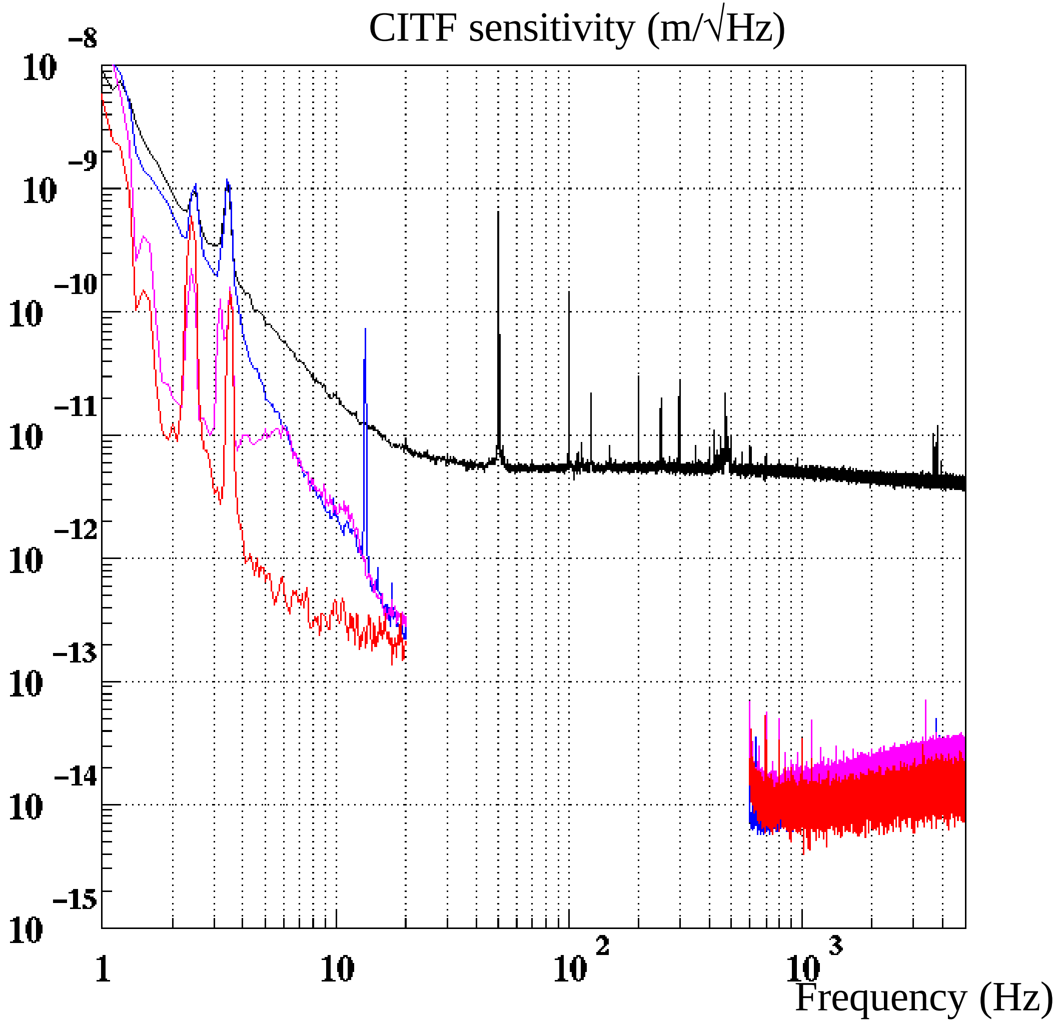
- electronics noise

- laser frequency noise

- Small variations depending on:

- laser power

- unity gain on frequency stab.

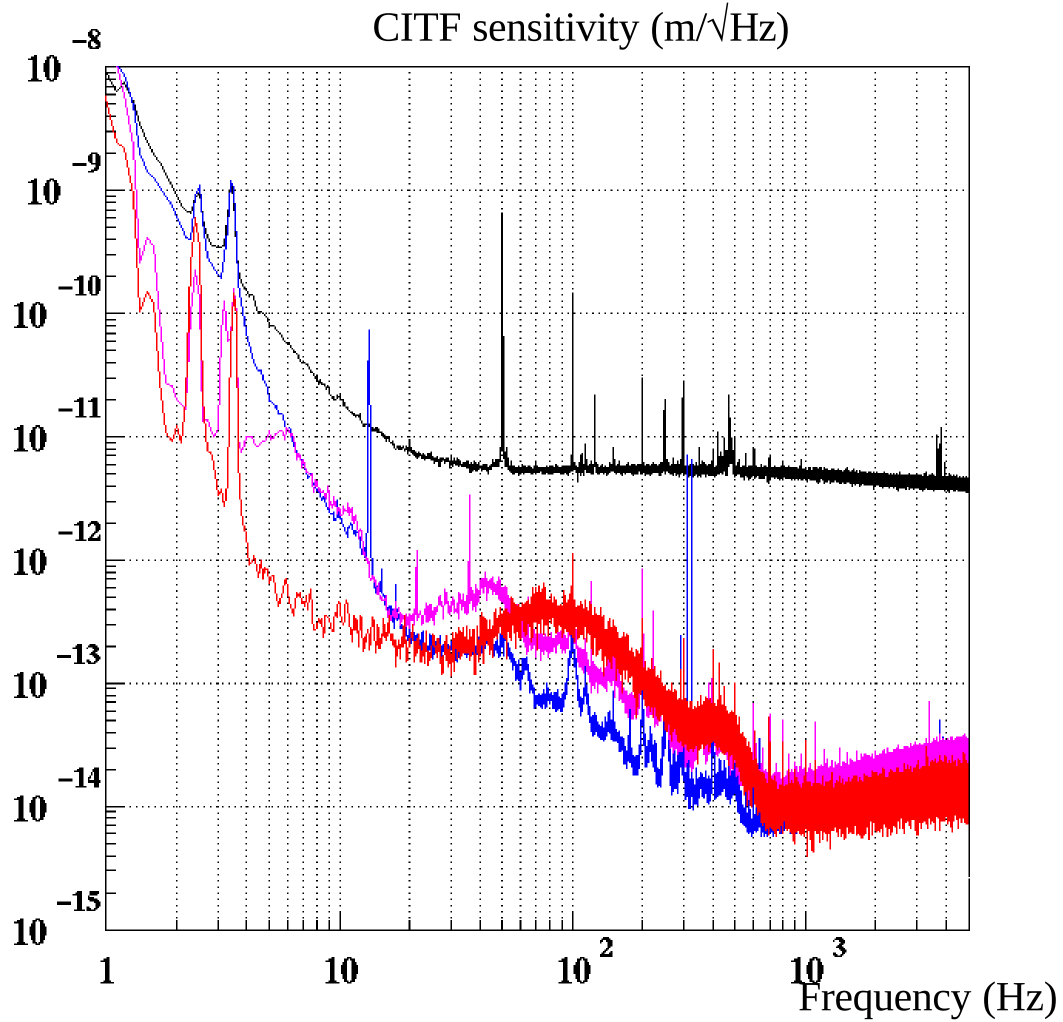


Sensitivity studies:10 Hz - 600 Hz

• Large sensitivity variations in this region of frequencies

• Variations correlated with change in the alignment

⇒ change in common mode rejection



Automatic alignment implementation

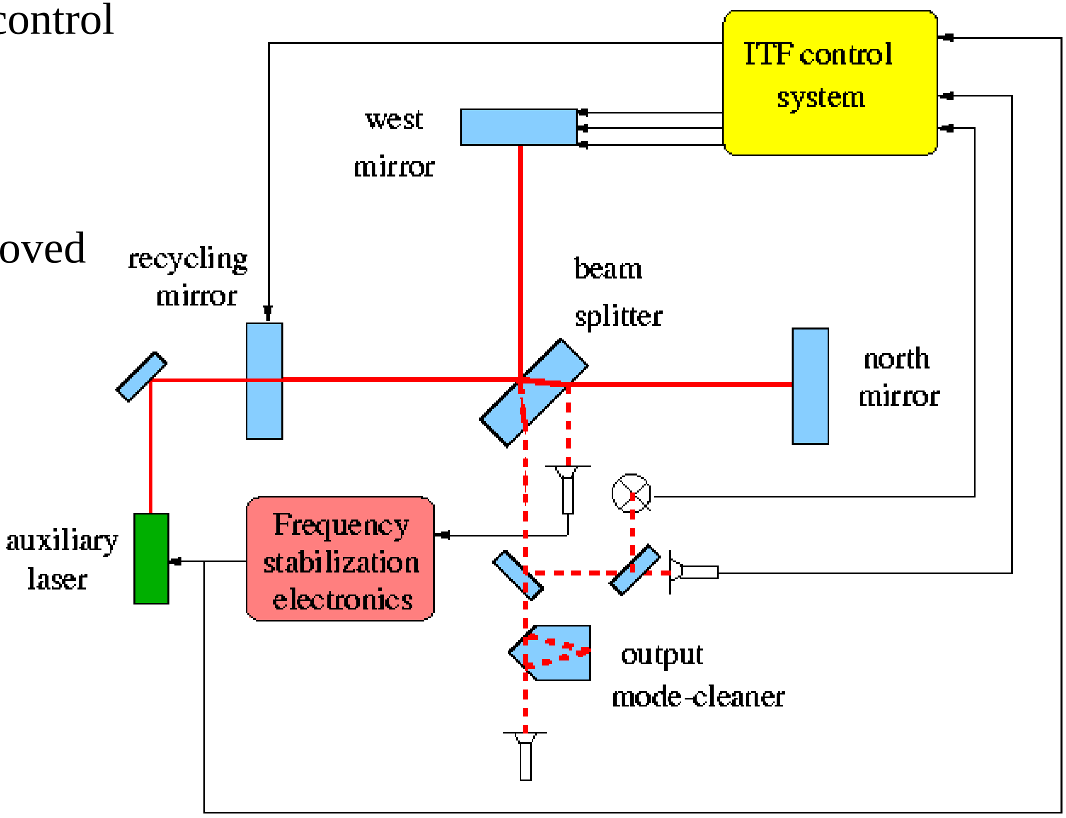
• Need for a better alignment

• Use quadrant on dark fringe to control west mirror alignment

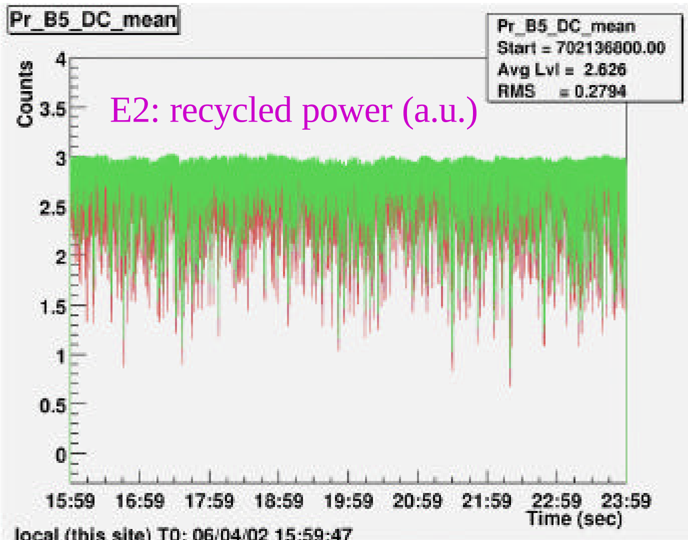
⇒ Recycled power stability improved

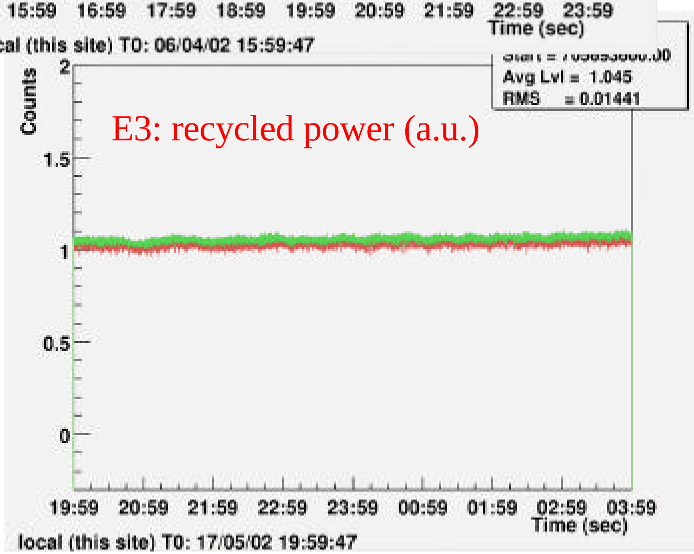
⇒ Sensitivity stability improved

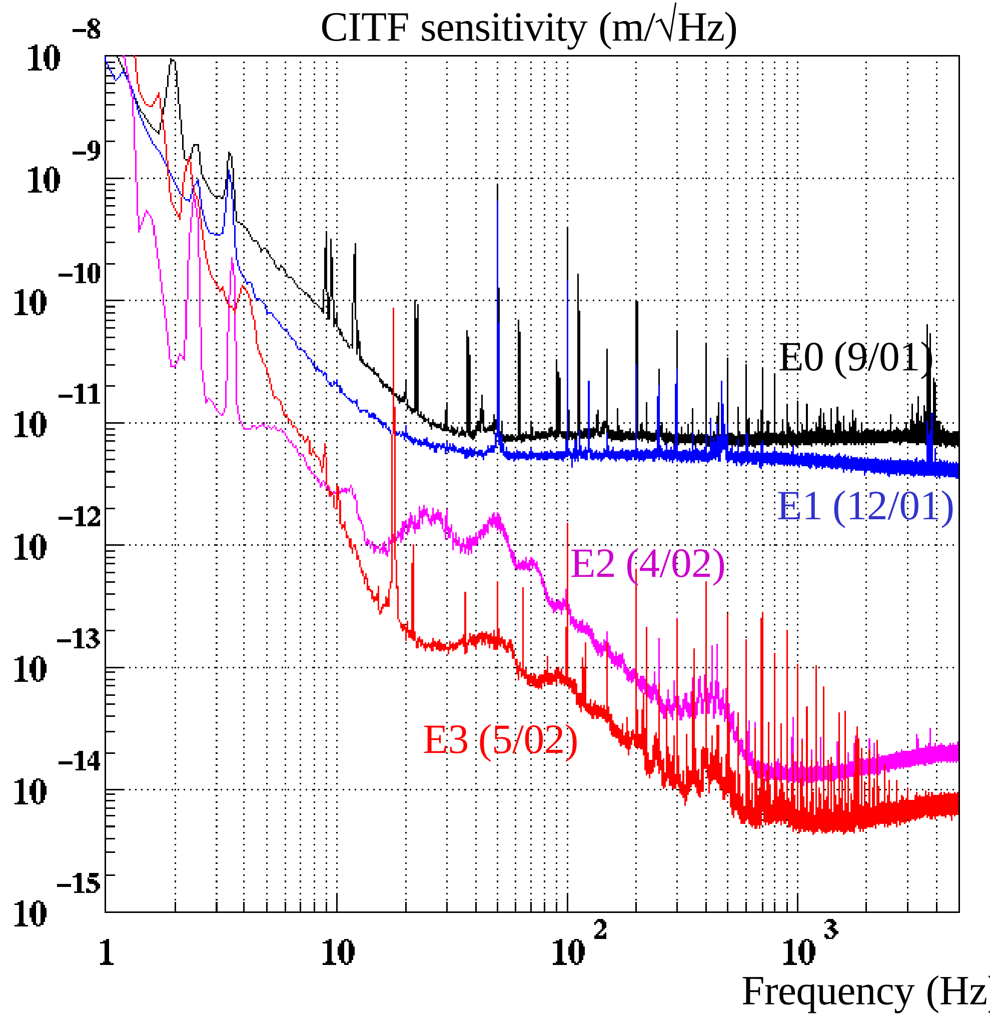
⇒ Output mode-cleaner easily locked on the dark fringe



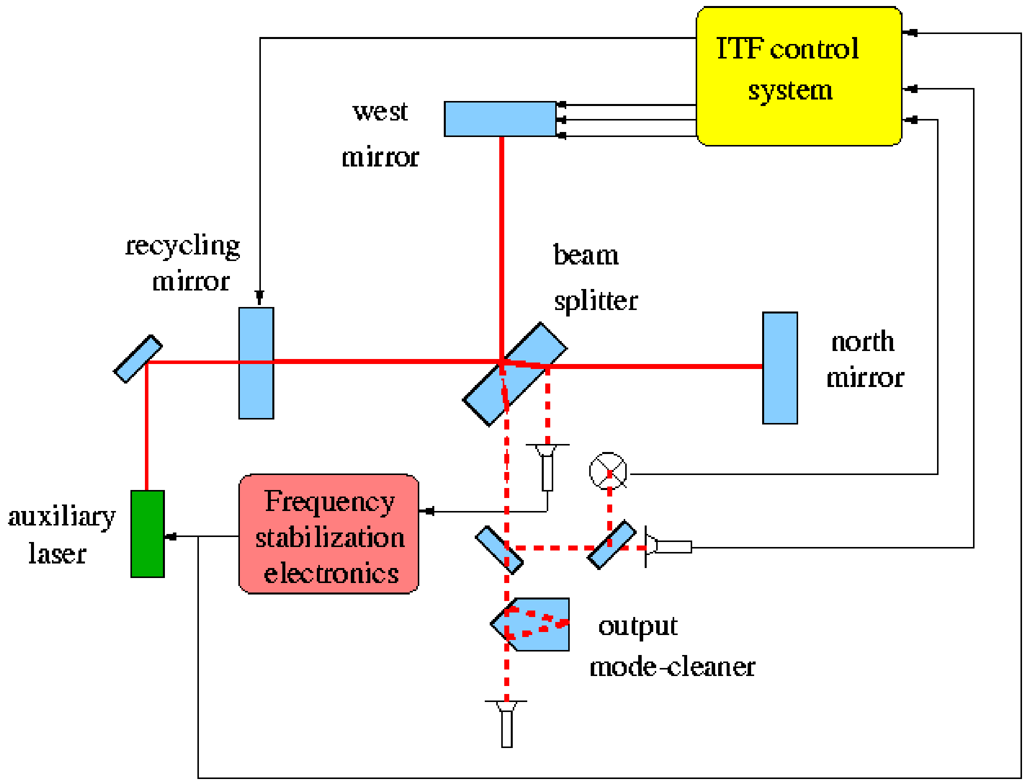
Automatic alignment effect: E2 vs E3







Injection system integration



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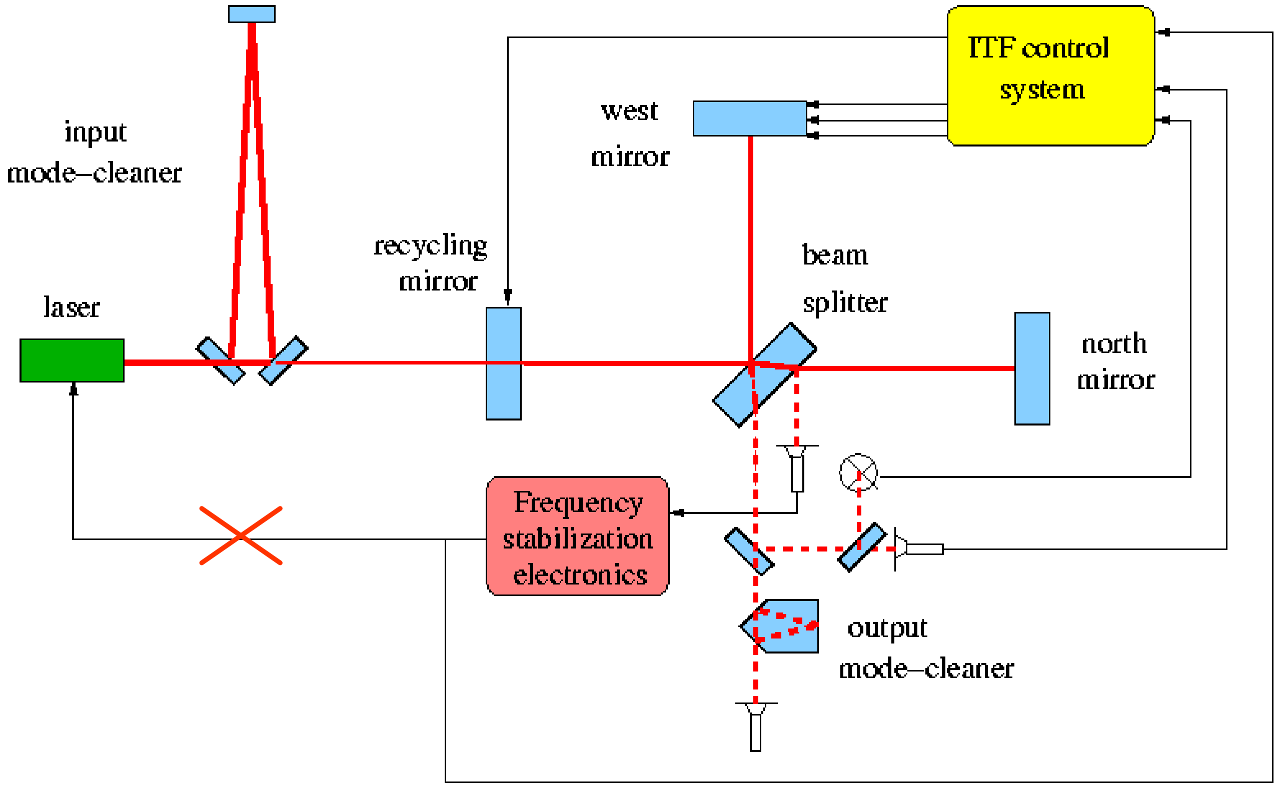
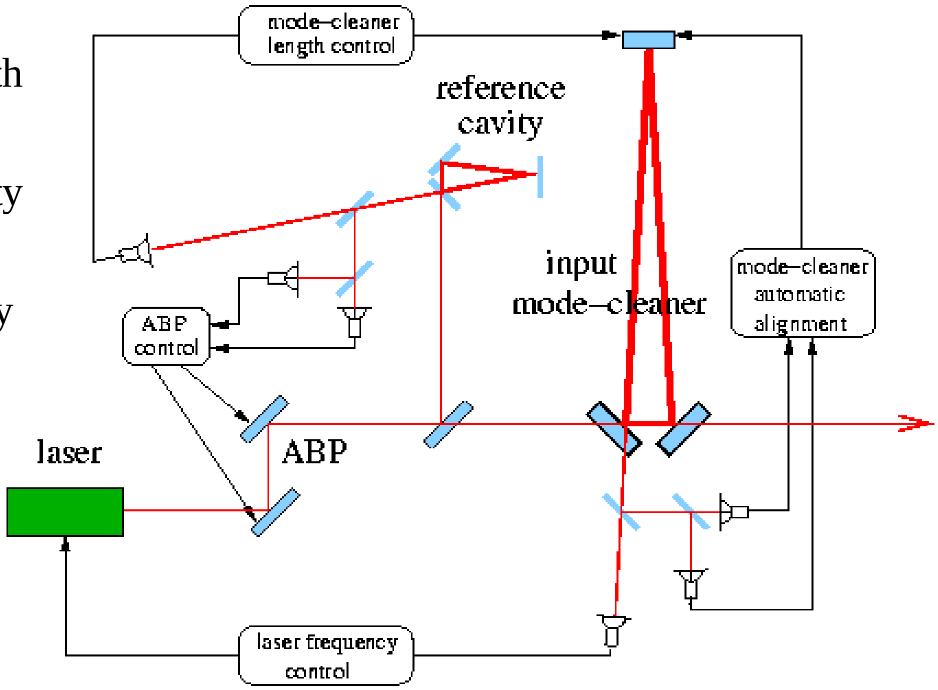


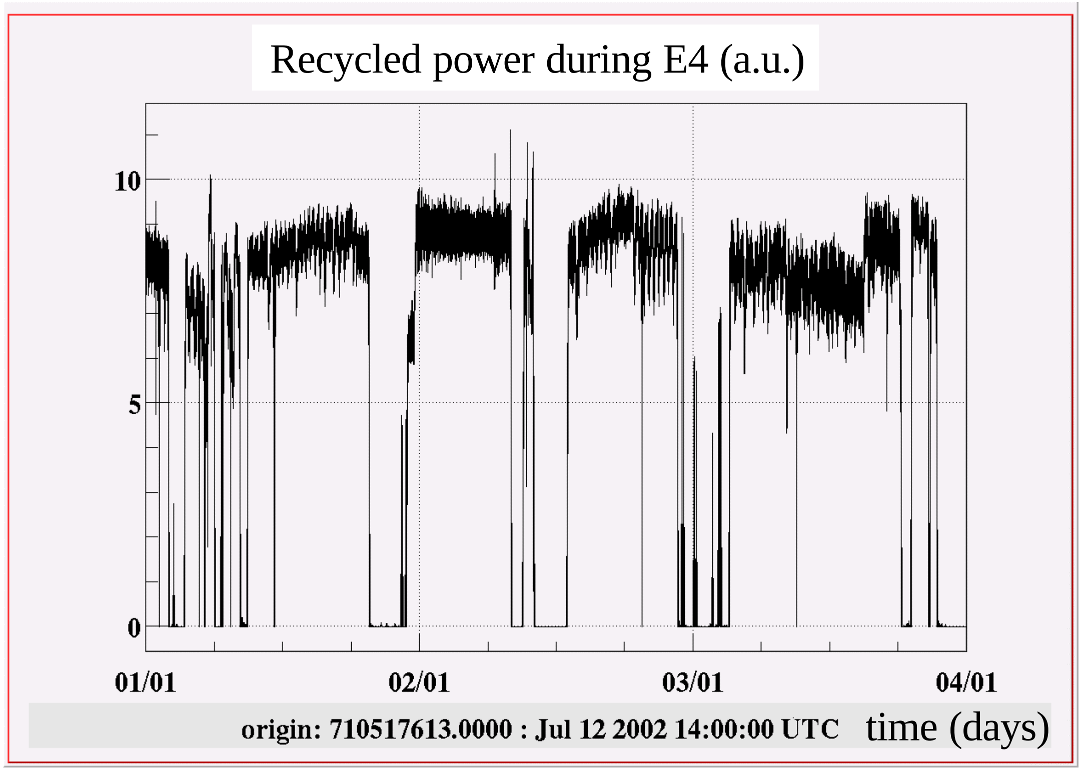
Injection system configuration

- Laser frequency locked to mode-cleaner length
- Mode-cleaner length locked to reference cavity
- Beam automatic alignment on reference cavity
- Automatic alignment of mode-cleaner mirror
- Laser power stabilization



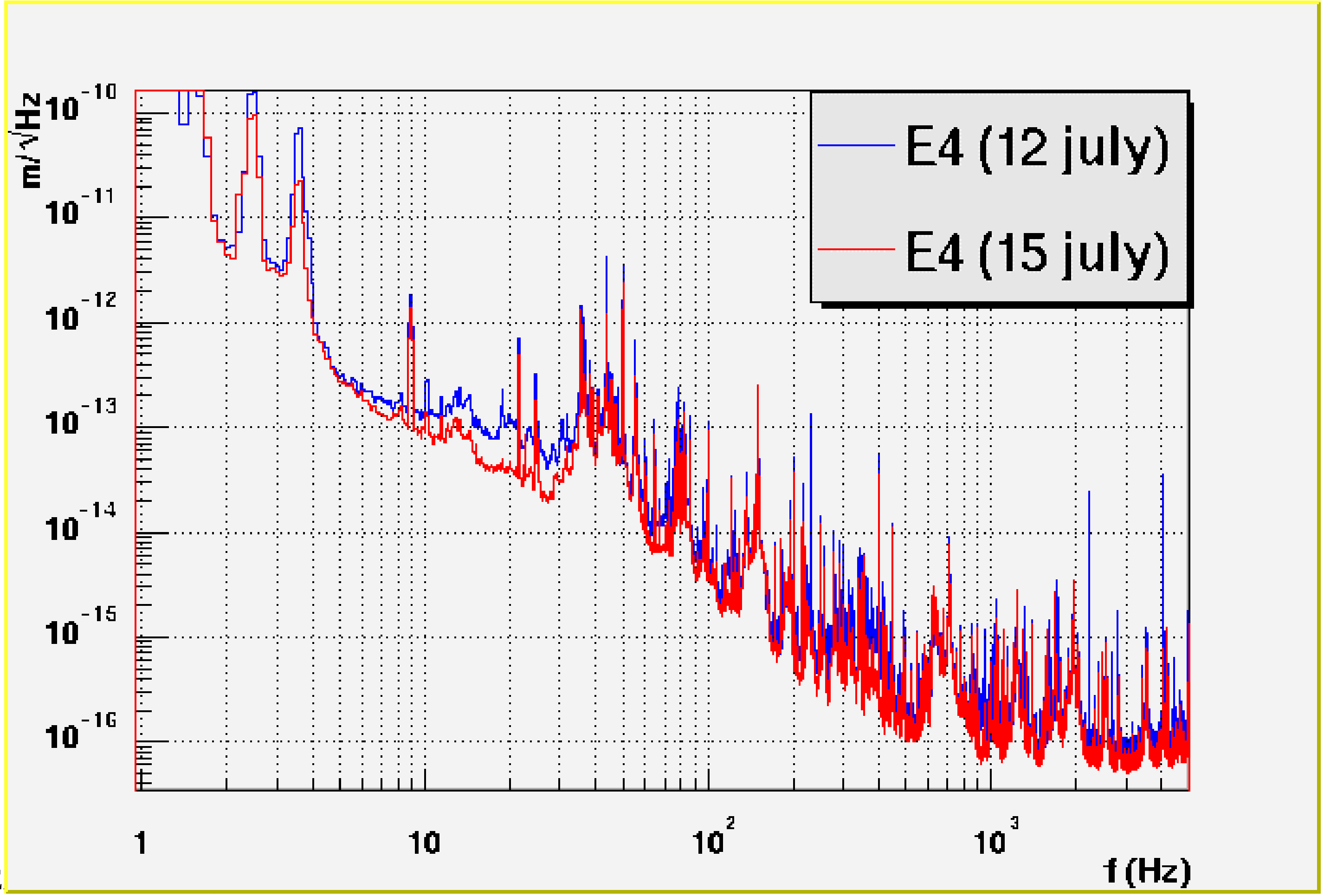
E4 duty cycle

- Duty cycle during E-runs:
- E0 ~ 98%
- E1 ~ 85%
- E2 ~ 98%
- E3 ~ 98%
- E4 ~ 73%



- Smaller duty cycle (expected)
- Lock acquisition more difficult
- Due to back-reflected light from ITF to injection (unexpected)

E4 sensitivity



E4 sensitivity studies

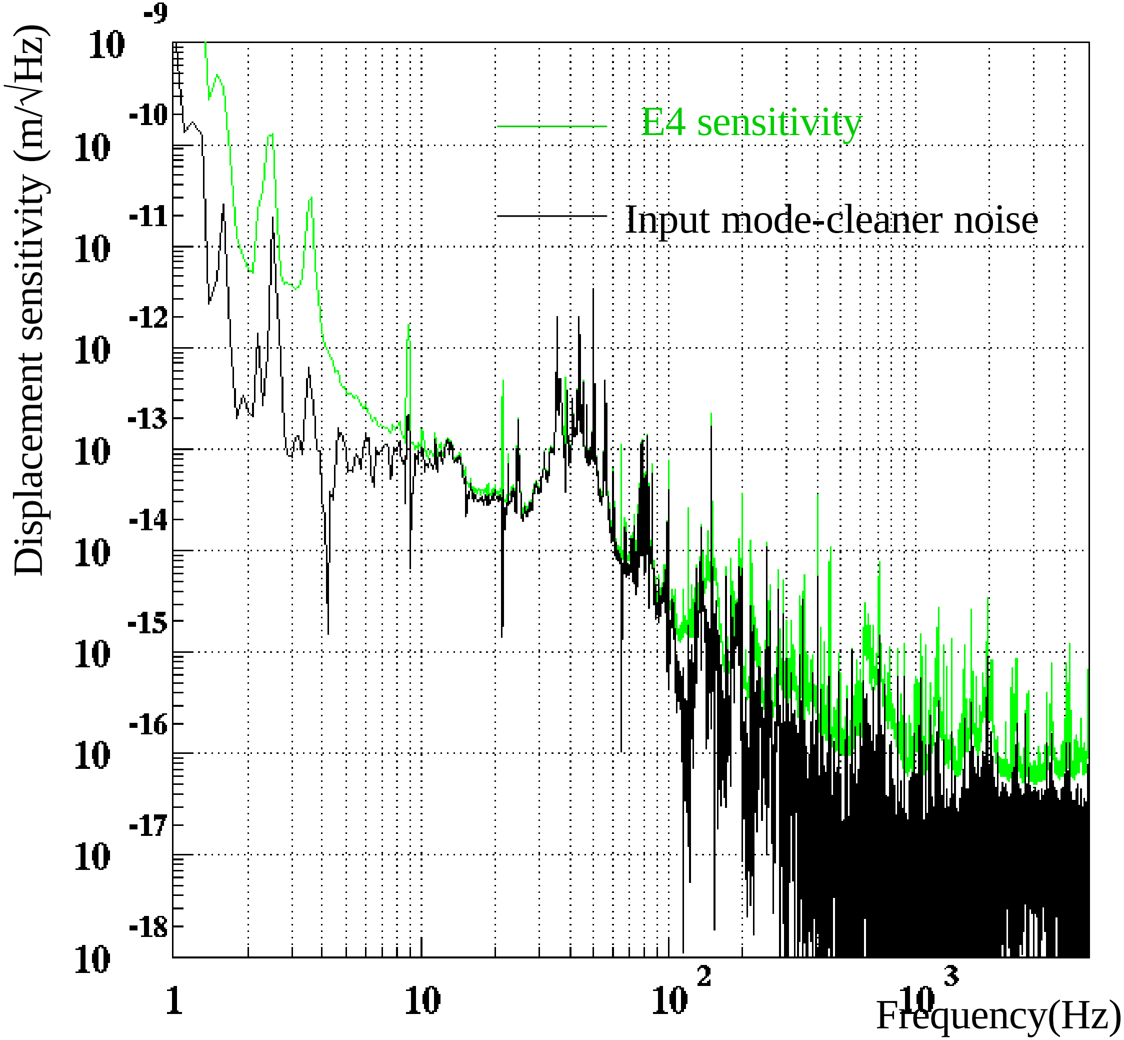
Noise budget

- f < 10 Hz
Angular control noise

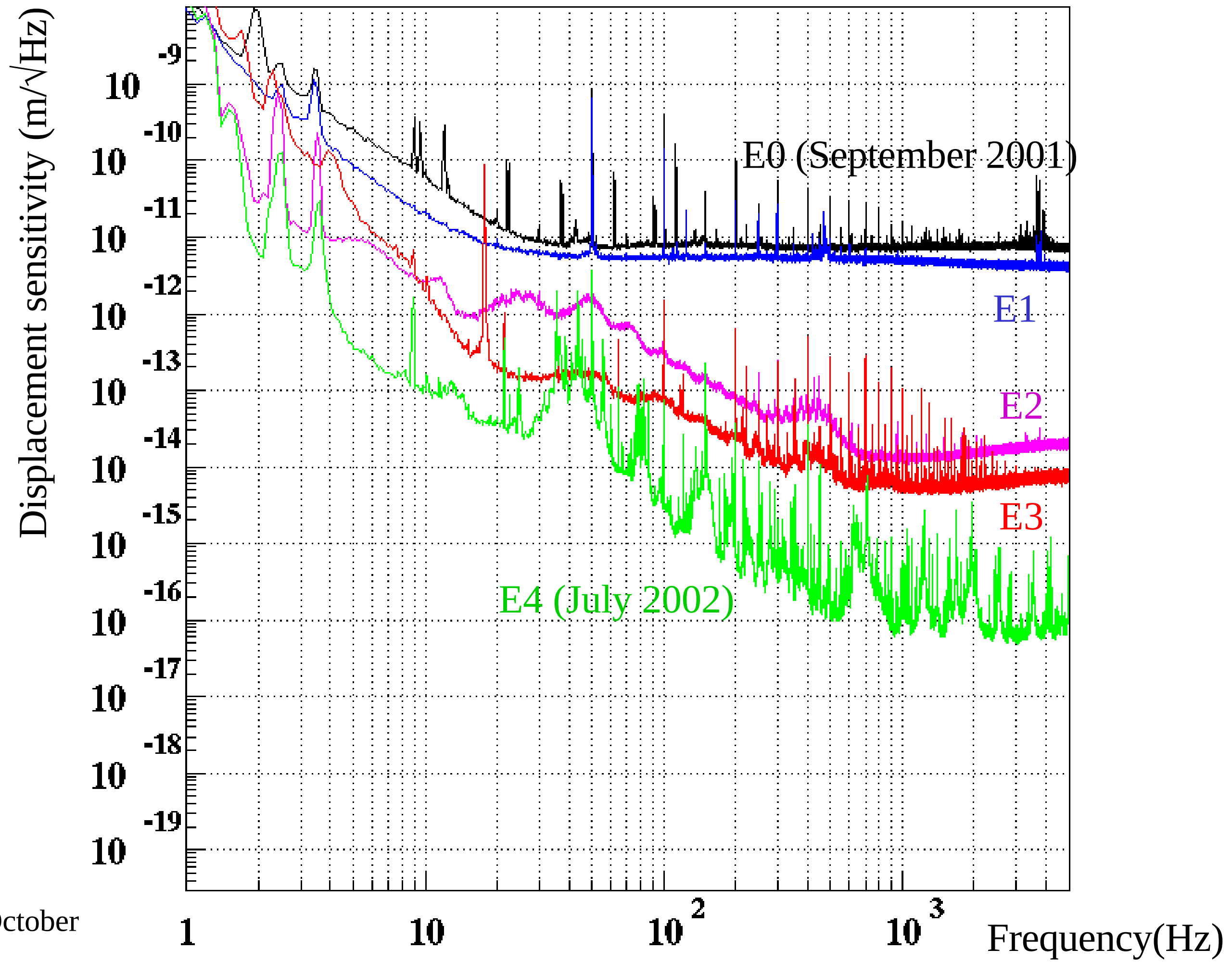
- 10 Hz < f < 200 Hz
Input mode-cleaner noise

- f > 200 Hz
Several peaks due to payloads internal resonance's

Work in progress



Summary of CITF sensitivity



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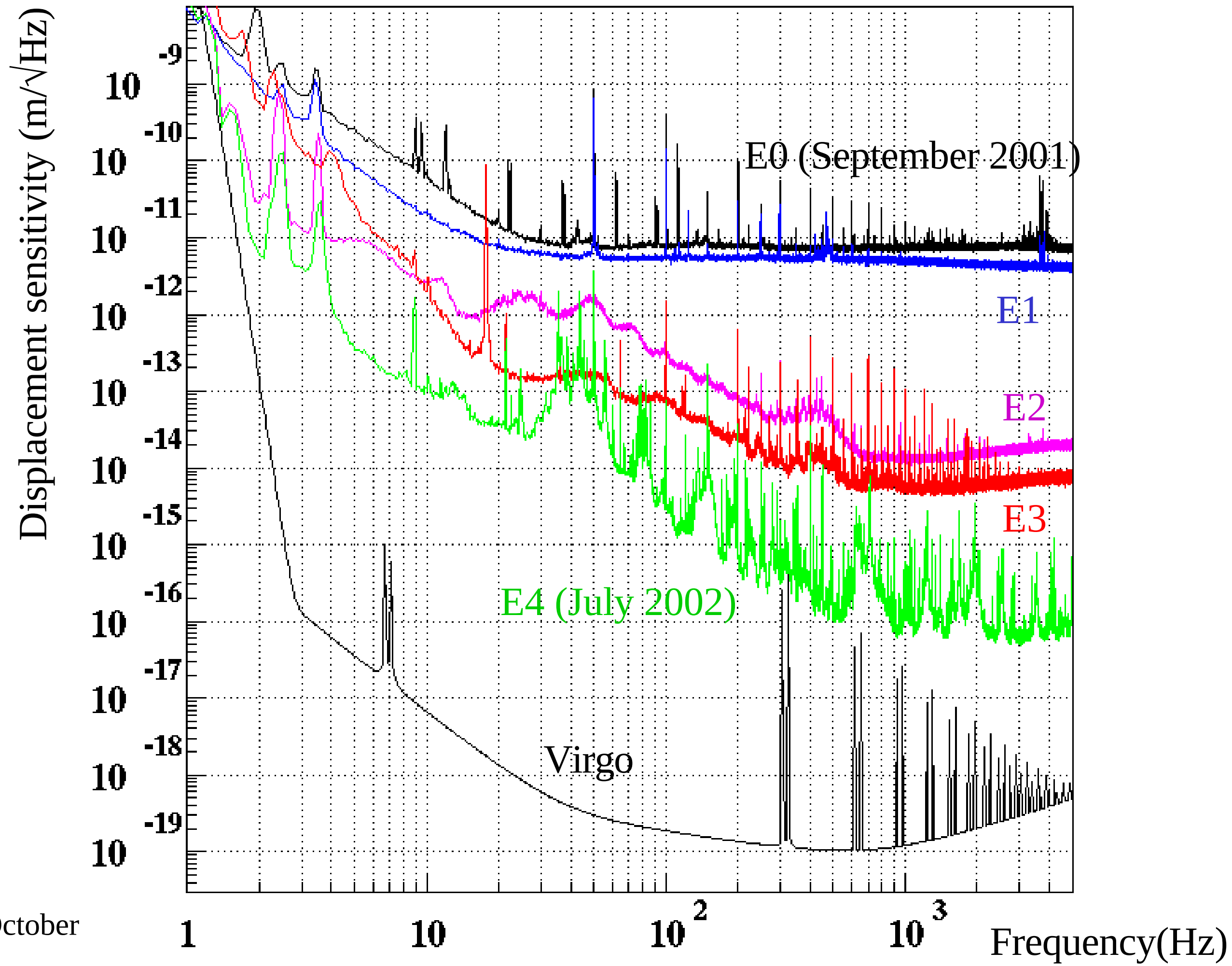

Conclusions and Perspectives

• CITF shut down last July

• Results:

- Final sensitivity: 10^{-13} m/√Hz @ 10 Hz and better than 10^{-16} m/√Hz @ 1 kHz
- Noise: identified over a large part of the spectrum
- Reliability: sources of ITF lock losses identified
- A lot of experience gained, many bugs discovered

• Several changes to the detector design triggered

- local control improvements
- input mode-cleaner design & control
- …..

• Fight against technical noise will start again next year with full Virgo