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EGO

On Aspects of the Advanced Virgo Arm Cavity Design

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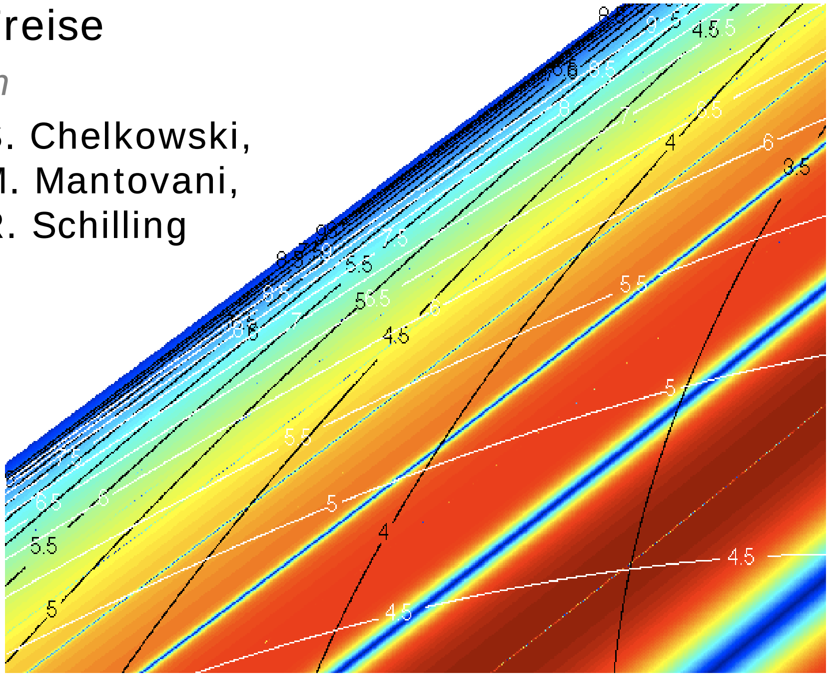
with input from F. Bondu, A. Brillet, S. Chelkowski, J. Degallaix, G. Losurdo, C.N. Man, M. Mantovani, J. Marque, G. Mueller, L. Pinard, R. Schilling and others ...



LSC-Virgo meeting Amsterdam, September 2008

LIGO-G080523-00-Z

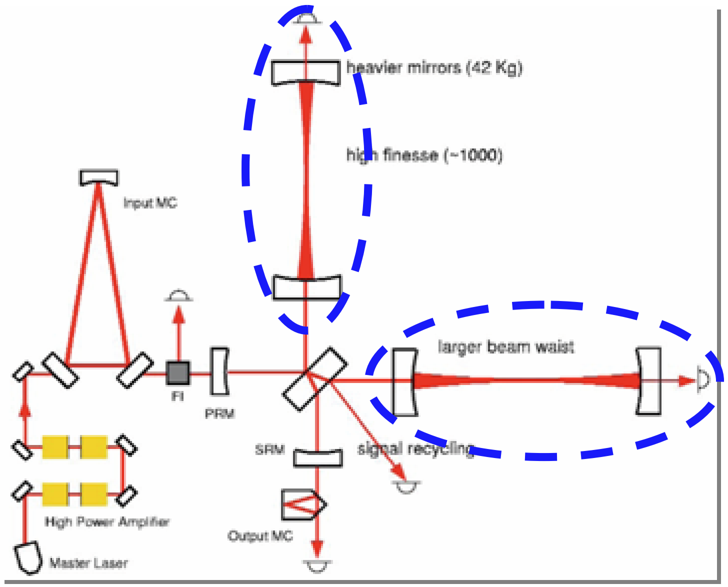
The Context

- Advanced Virgo design is organized in several subsystems.
- I work on the subsystem: “Optical simulation and Design” (OSD) *subsystem-manager: A. Freise*
- One of the primary tasks of the OSD-subsystem is the **Advanced Virgo Arm Cavity Design.**

Arm Cavities: The Core of GW Detectors

- In principle arm cavities are rather simple objects, consisting of just two mirrors and a space between them.

- In reality one has to carefully choose the characteristics of the arm cavities:
  - Detector sensitivity and bandwidth.
  - Actual arm cavity design sets constraints for other subsystems.
  - Design of other subsystems sets constraints for the arm cavity design.



Characteristics of the Arm Cavity to be chosen

- Beam geometry (waist position)
- Beam size at the test masses
- Radius of curvature of the test masses
- Finesse of the arm cavity

} Brief overview of the principle considerations

- Wedges or Etalon

} … going a bit more into detail … (Discussion of various requirements and constraints)

Beam Geometry

- Where to put the waist inside the arm cavity?
  - Initial detectors have the waist close/at the input mirrors
- Advanced detectors: Move waist towards the cavity center.
  - Larger beam at input mirror
  - Lower overall coating Brownian noise
  - BUT: much larger beams in the central interferometer
    - may need larger BS
    - much larger optics for input and output telescope
    - Non-degenerate recycling cavities might help

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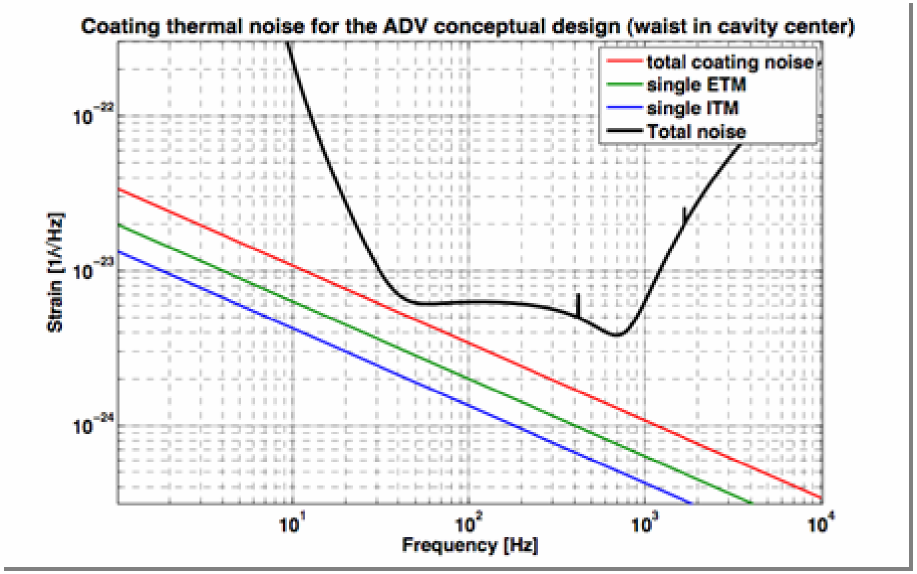
Beam Geometry

- Intuitively one would think the lowest coating noise is achieved when beam waist is at the center of the cavity (=> equal beam size at ITM and ETM),
  BUT:

- Coating noise for ITM and ETM are different, due to their different number of coating layer:

$$\bar{v} = C(S_T + \gamma^{-1} S_S),$$

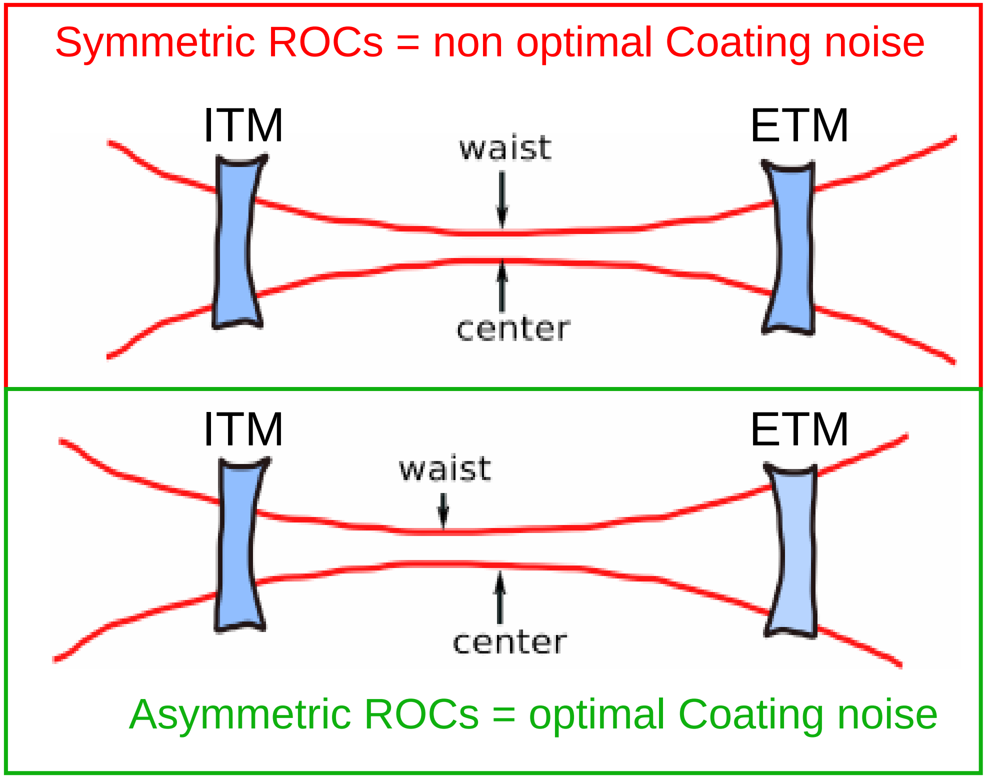
J. Agresti et al (LIGO-P060027-00-Z)



- For equal beam size ETM has higher noise.

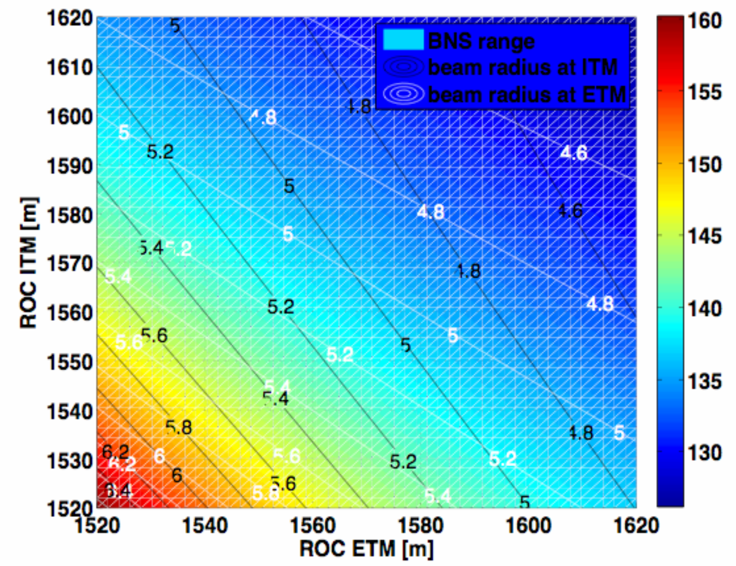
Optimal Waist Position

- In order to minimize the thermal noise we have to make the beam larger on ETM and smaller on ITM.
- Equivalent to moving the waist closer to ITM.
- Nice side effect, the beam in the central central area would be slightly smaller.



Beam Size

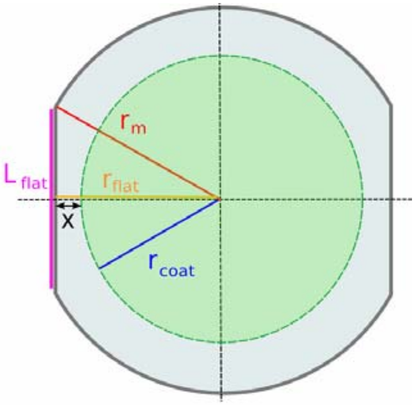
- Principle Rule:
  - The larger the beam the better the detector sensitivity
  - Larger beams make nearly everything else more complicated / more expensive.
- Advantages of large beams:
  - Reduced thermal noise of test masses (especially coating Brownian)
  - Slightly reduced contribution from residual gas pressure
  - Reduced thermal lensing



- Disadvantages of large beams:
  - Higher clipping losses
  - Larger test masses (especially BS, because of 45deg angle)
  - Larger apertures are required (vacuum system, actuators, etc)
  - Large telescopes (input, output, pick-off beams)
  - More sensitive to ROC deviations

How to decide on Beam Size ?

- Order of constraints:
  1. Mirror weight (from suspension)
  2. Aspect ratio of mirror
  3. Coating size
  4. Choose affordable losses



- Final decision needs to trade off:
  - Detector sensitivity
  - Clipping losses inside the arm cavity (mirror/coating size)
  - Clipping losses inside recycling cavities (actuator geometry, BS size)
  - Scattered light noise contribution of the clipped light
  - Cavity stability (see following slides)

- In the end we will probably choose a beam radius (1/e^2 in power) of about 5.5 to 6.5cm.

More detail in
Hild et al: VIR-038B-08

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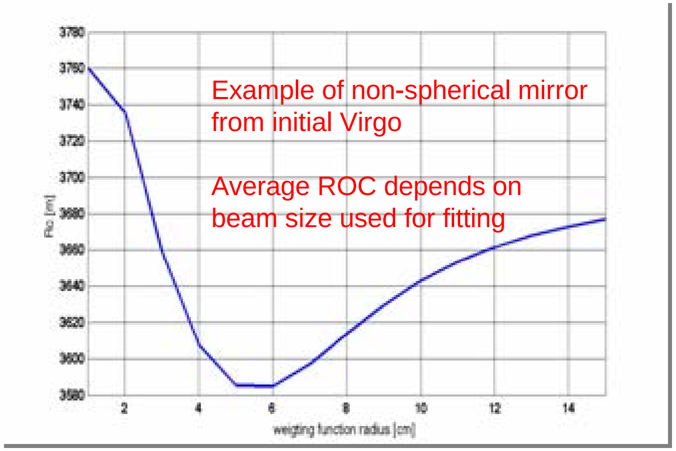
Cavity Stability and Choice of ROCs

- ROCs and beam size are connected.
- We want ROCs that give stable cavity:
  - Account for potential manufacturing accuracy
    - AdVirgo example: L = 3000m, beam radius at ITM and ETM = 6cm => ROCs of 1531m are required.
    - Deviation of only a few ten meters can make cavity instable.
    - Additional problem: polished spheres are not spherical.



  - Avoid resonance of higher order optical modes
    - Use mode-non-degeneracy as figure of merit

Cavity Stability and Choice of ROCs

- Definition of mode-non-degeneracy:
  - Gouy-phase shift of mode of order l+m:

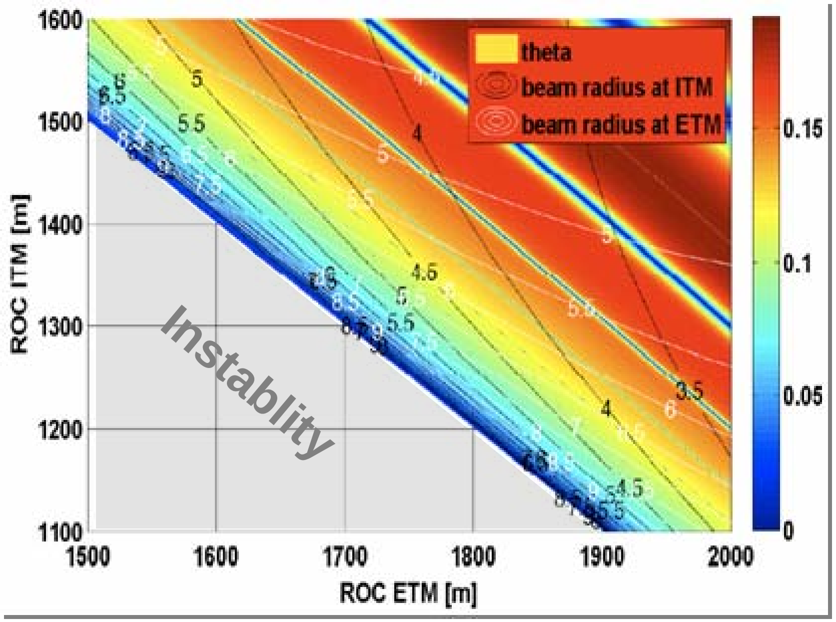
$$\phi_{l+m} = (l+m)\frac{1}{\pi}\arccos\sqrt{(1-\frac{L}{R_{c,i}})(1-\frac{L}{R_{c,e}})}.$$

  - Mode-non-degeneracy for a single mode is:

$$\Psi_{l+m}(L, R_{c,i}, R_{c,e}) = |\phi_{l+m} - \mathrm{round}(\phi_{l+m})|.$$

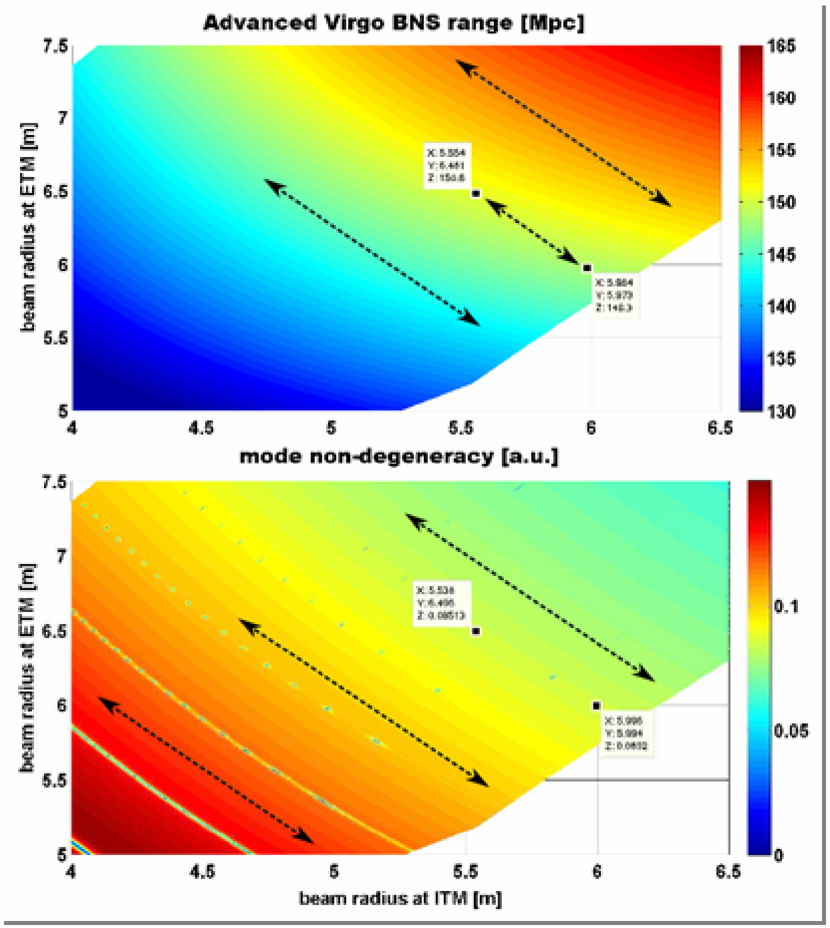
  - Figure of merit for combining all modes up to the order N:

$$\Theta_N(L, R_{c,i}, R_{c,e}) = \frac{1}{\sqrt{\sum_{k=1}^{N} \frac{1}{\Psi_k^2}\frac{1}{k!}}}$$



Choice of ROCs/beam size: Sensitivity vs Mode-non-degeneracy

- In general mode-non-degeneracy and sensitivity go opposite.
- Asymmetric ROCs are beneficial:
  - For identical mode-non-degeneracy (parallel to arrows in lower plot) we can increase sensitivity (parallel to arrow in upper plot) by going towards the upper left corner.
  - This means making beam larger on ETM and smaller on ITM.



Arm Cavity Finesse

- Advantages of higher finesse:
  - Reduced noise coupling from MICH to DARM
  - Less thermal load in central interferometer
- Disadvantages of higher finesse:
  - More sensitive to losses inside the arm cavities
  - Increased coating Brownian noise of the ITM (due to more required coating layers
  - Power problems (parametric instabilities)?
- In the end we will probably go for a finesse between 400 and 700.

Characteristics of the Arm Cavity to be chosen

- Beam geometry (waist position)
- Beam size at the test masses
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} Brief overview of the principle considerations

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} … going a bit more into detail … (Discussion of various requirements and constraints)

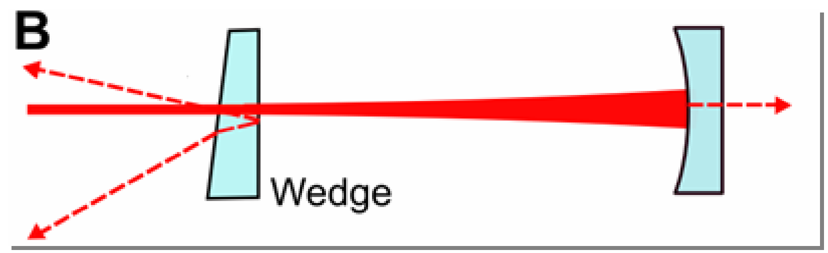
Wedges vs Etalon

Input mirror etalon:

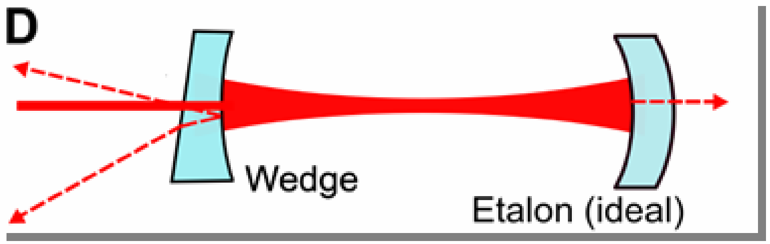
- Initial Virgo has no wedges in the input mirrors
- The etalon effect could be used for adjusting the cavity finesse (compensating for differential losses)
- If etalon effect is not controlled it might cause problems

Input mirror with wedge:

- Used by initial LIGO
- Reflected beams from AR coating can be separated from main beam => pick-off beams provide additional ports for generation of control signals.
- No etalon effect available.



Possible design option: Wedges at input mirrors and etalon effect at end mirrors



- Wedge at input mirrors:
  - Allows for additional pick-off beams
- Use etalon effect at end test mass
  - Tune etalon to balance arms => reduce noise couplings => might speed up commissioning
  - Tune etalon to change readout quadrature in DC-readout.
  - Replace AR-coating by a coating of about 10% reflectivity.
  - Ideally use a curved back surface (same curvature as front).

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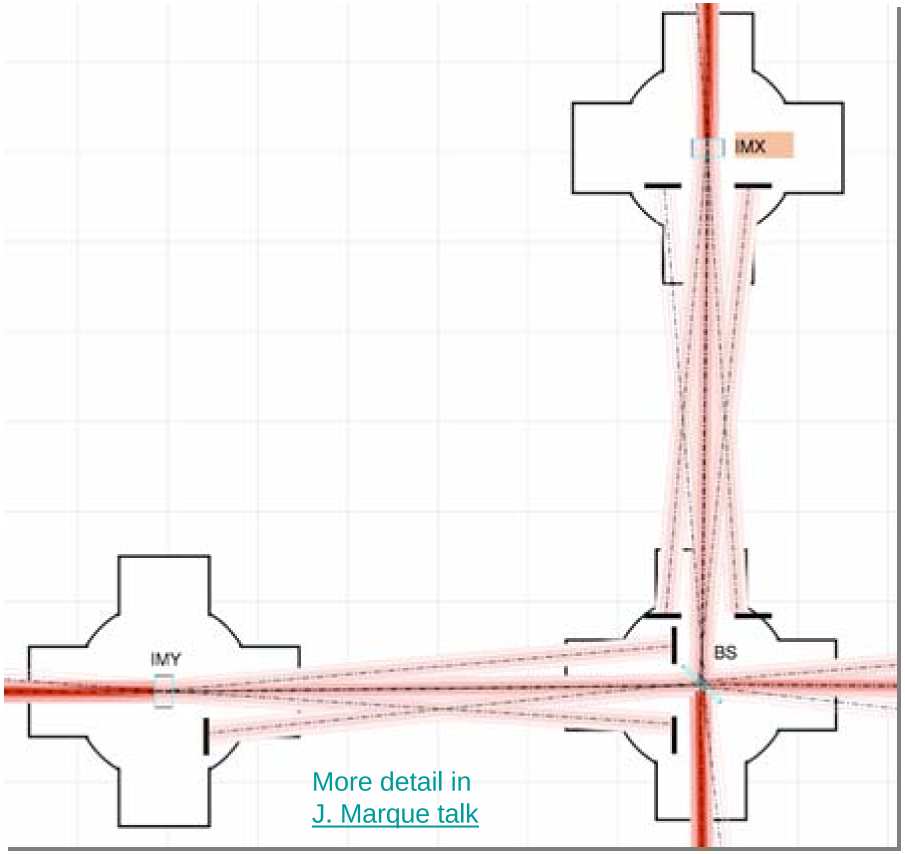
Wegdes at Input Mirrors

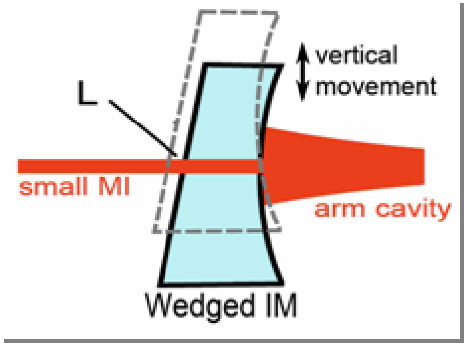
- Need a wedge large enough to separate beams within about 5 meter (distance ITM to BS).
- For 6cm beam radius a wedge of about 1.5 deg is required.
- High hardware impact (larger vacuum tube in centeral IFO, more optical elements)



More detail in
J. Marque talk

Differential Arm Length Noise from vertical Movement of wedged Input Mirrors

- Lateral movement of a wedged mirror cause length sensing noise.



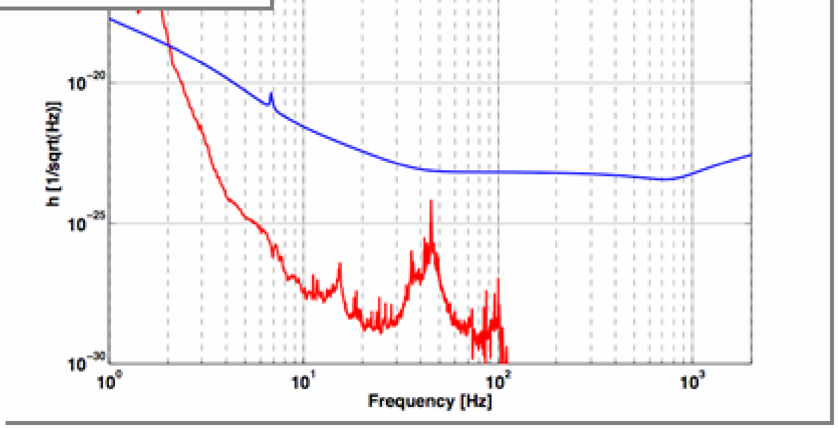
- Need to do a projection of seismic noise to DARM:

$$h_{\text{wedge}} = 2 \cdot \tilde{V}_{\text{sei}} \cdot TF_{\text{SA}} \cdot \tan(\alpha) \cdot (n_{\text{sub}} - 1) \cdot \frac{\pi}{2F} \cdot \frac{1}{3000\,\text{m}}$$

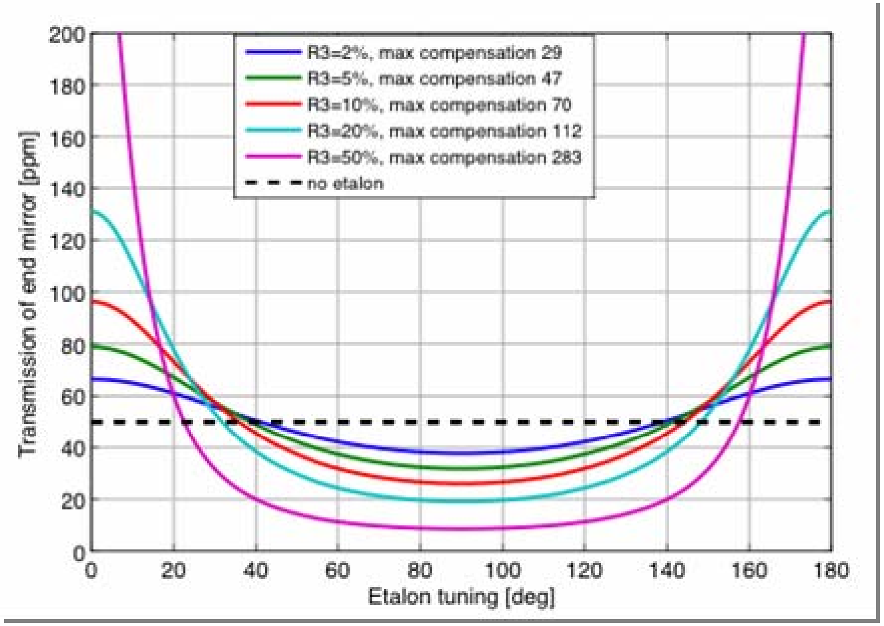
More detail in
Hild et al: VIR-037A-08

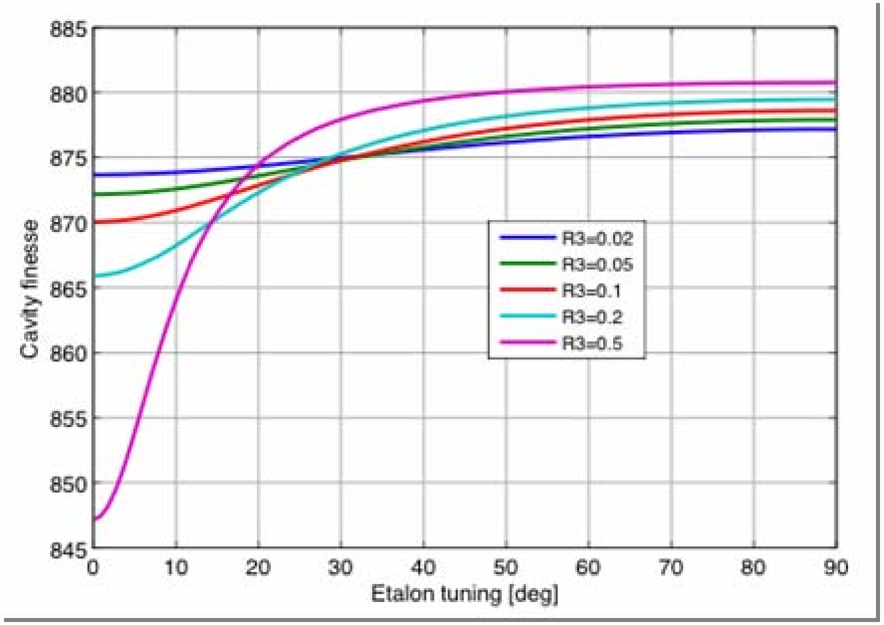
- Not limiting within the detection band.

- Please note: No actuation noise considered.



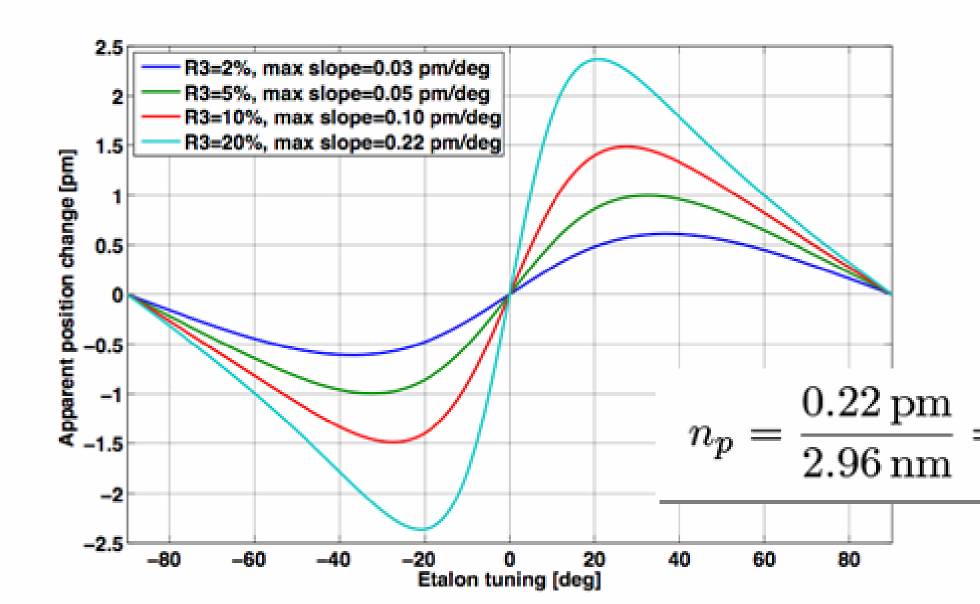
Balancing Range due to Etalon Effekt





- Examples of figures of merit:
  - Transmittance of end mirror (etalon)
  - Finesse of arm cavity

Etalon changes Optical Phase



$$n_p = \frac{0.22\,\mathrm{pm}}{2.96\,\mathrm{nm}} = 7.4 \times 10^{-5}$$

- When changing the etalon tuning the optical-phase changes as well. (noise!)
- The two etalon surfaces build a compound mirror, whose apparent position depends on the etalon tuning.

Requirement for Temperature Stability of Etalon Substrate

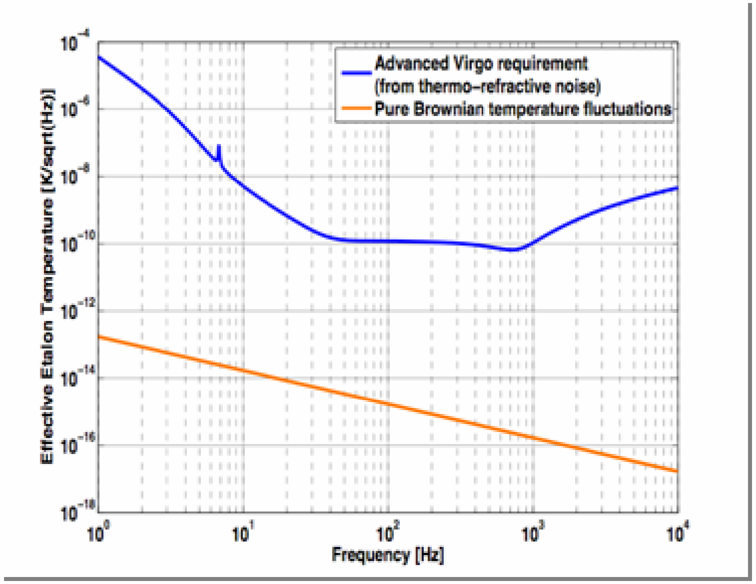
- Certain temperature stability of Etalon substrate required to not spoil AdV sensitivity

$$\tilde{h}_{\rm adv}(f) = \tilde{T}_{\rm req}(f) \cdot \frac{dn}{dT} \cdot l_{\rm eta} \cdot n_p \cdot \frac{1}{L},$$

- Can compare this requirement to substrate thermal noise

$$\tilde{T}_{\rm mirror}(f) = \sqrt{\frac{4 k_b T^2 \kappa}{(\rho C)^2 l_{\rm eta}} \frac{1}{\pi R_b^4 (2\pi f)^2}},$$

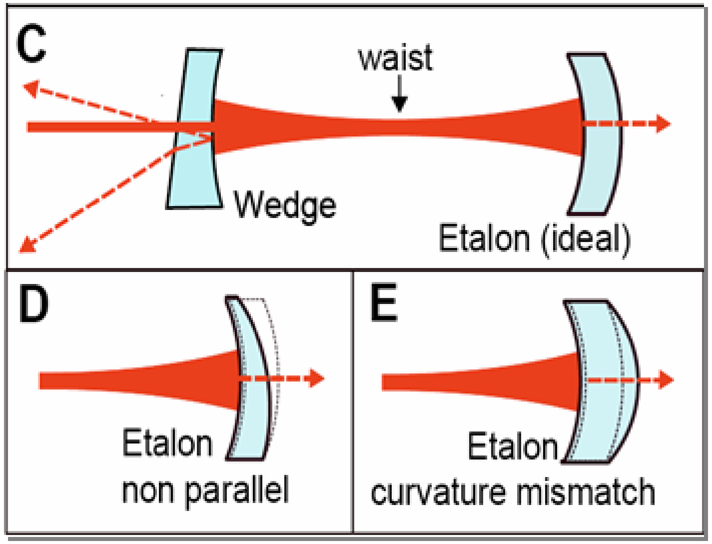
- Not limiting.
- Please note: Did not consider technically driven temperature fluctuations.



More detail in
Hild et al: VIR-058A-08

Optical Design: Check System Integrity for Deviations from Specs

- A deviation in the relative misalignment (parallelism) and relative curvature of the two etalon surfaces:
  - Imperfect wave front overlap...
  - Reduces tuning range ...
  - Beam shape distortions ...



- Two methods for analysis:
  - FFT based code (Waveprop)
  - Coupling coefficients

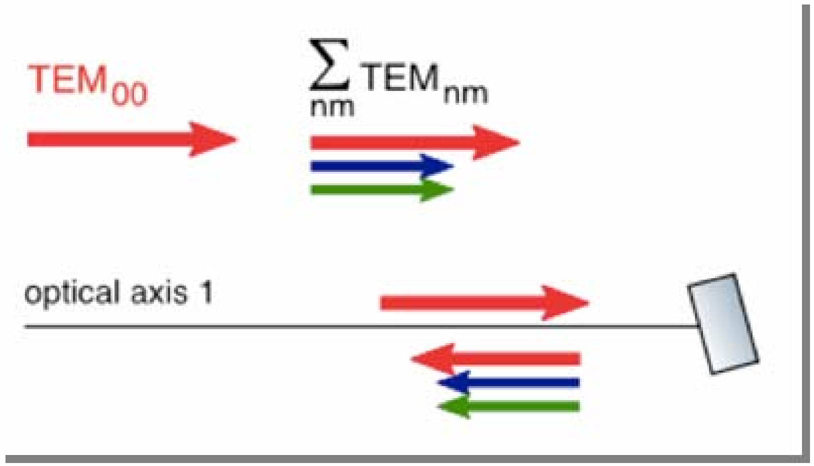
FFT-simulation of a Non-Perfect Etalon

- Using R. Schilling's WaveProp, http://www.rzg.mpg.de/~ros/WaveProp/
- Cross checking with DarkF. DarkFstatus_08_03_2006.ppt
- Parameters:
  - Field: 256x256
  - Computing 3000 roundtrips
  - End mirror front:
    - 50ppm transmission
  - End mirror back:
    - Varying three parameters
    - **Reflectance**
    - **Misalignment** (parallelism)
    - **Curvature mismatch**

```
!   Set parameters:
     sog    = .400                 ! size of the grid in one dimension [m]
     lambda = 1.064e-6             ! light wavelength [m]
     dist   = 3000.                ! mirror distance [m]
     wi     = .03517543                 ! radius of initial beam [m]
     m1%dx  = 0.175                ! radius of cavity input mirror M1 [1/m]
     m1%c   =-1./1910.             ! curvature of cavity input mirror [1/m]
     m1%r   = sqrt(0.9929)            ! amplitude reflectance of cavity input mirror
     m2fr   = m1
     m2fr%r = sqrt(0.99995)
     m2fr%n2= 1.44963              ! refractive index of end mirror substrate
     m2ft   = m2fr
     m2b%dx = 0.175                ! radius of rear surface of M2 [1/m]
     m2b%c  = 0.                   ! curvature of rear surface of M2 [1/m]
     m2b%r  = sqrt(0.20)           ! amplitude reflectance of rear surface of M2
     m2b%n1 = m2fr%n2              ! refractive index of end mirror substrate
!
     call wp_init(nx,sog,lambda,fftw='m')            ! initialize WaveProp
!
     call wp_setup(m1)                          ! set up cavity input mirror
     call wp_setup(m2fr)                        ! set up cavity end mirror (front surf.)
     call wp_setup(m2ft,'tf')                   ! set up cavity end mirror (front surf.)
     call wp_setup(m2b)                         ! set up cavity end mirror (back surf.)
     call wp_hgmode(psi_in,wi,-m1%c,pw=1-0.99295) ! generate initial field
!
     phi=0.
     do iph=0,nph                               ! do nph phase values for substrate
       phi=phi+(360./nph)*deg                   ! next phase for substrate cavity
       xp(iph)=iph*(360./nph)                   ! build array representing on X axis
       call wp_setup(psi_co)                    ! set up and clear cavity field
       call wp_setup(psi_su,m2fr%n2)            ! set up and clear substrate field
       do irt=0,nrt                             ! do nrt round trips
         x(irt)=real(irt)                       ! build array representing on X axis
         call wp_reflect(psi_co,m1)             ! reflect at near mirror
         call wp_interfere(psi_in,psi_co,psi_co,'c',pw_c=pw(irt))! constr. intrf.
         call wp_propagate(psi_co,dist) ! propagate to far mirror
         call wp_transmit(psi_co,m2ft,psi_out=psi_au)         ! emit though M2
         call wp_reflect(psi_su,m2fr,'b')                ! reflect @ rear of front surf.
         call wp_interfere(psi_au,psi_su,psi_su)  ! interference for su cavity
         call wp_reflect(psi_su,m2b,phi=phi)             ! reflect at back surface of M2
         call wp_transmit(psi_su,m2ft,'b',psi_out=psi_au)   ! emit though M2
         call wp_reflect(psi_co,m2fr)   ! reflect at front surface of M2
         call wp_interfere(psi_au,psi_co,psi_co)  ! interf. of co with su field
         call wp_propagate(psi_co,dist) ! propagate to near mirror
       end do
       pwc(iph)=pw(nrt)                         ! store final cavity power
     end do
!
     call wp_plot3d(psi_in,4,'Input field',zoom=2.)          ! plot input field
```

Analytic Approximations using Higher-Order Modes

- Reflection at a (slightly) misaligned component can be characterised by scattering into higher order TEM modes
- This model is valid for misalignments below half the diffraction angle (paraxial approximation)
- The amplitude in the outgoing fields is given by coupling coefficients k_{nmnm}



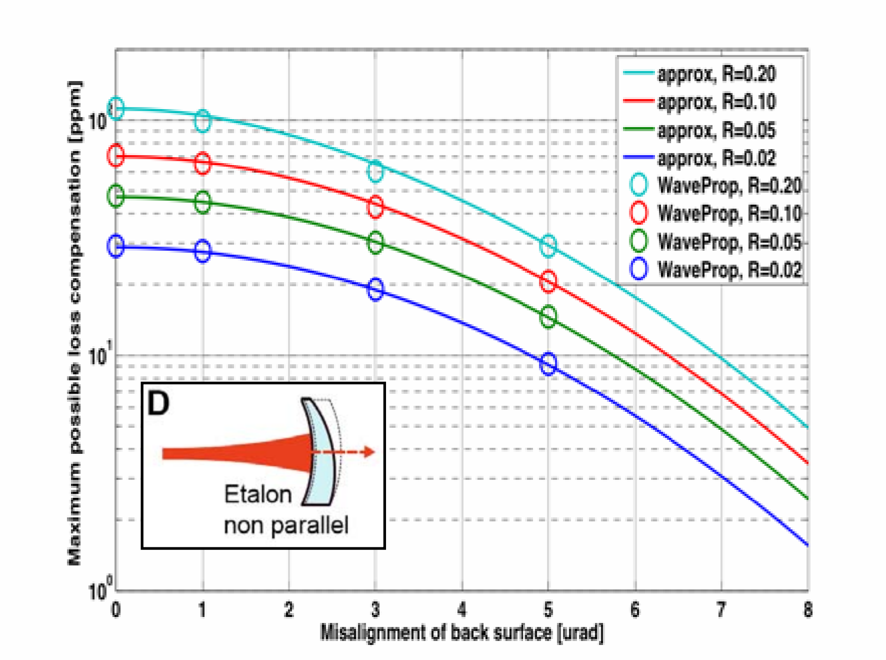
$$a_{nm} = k_{00nm}\ a_{00}$$

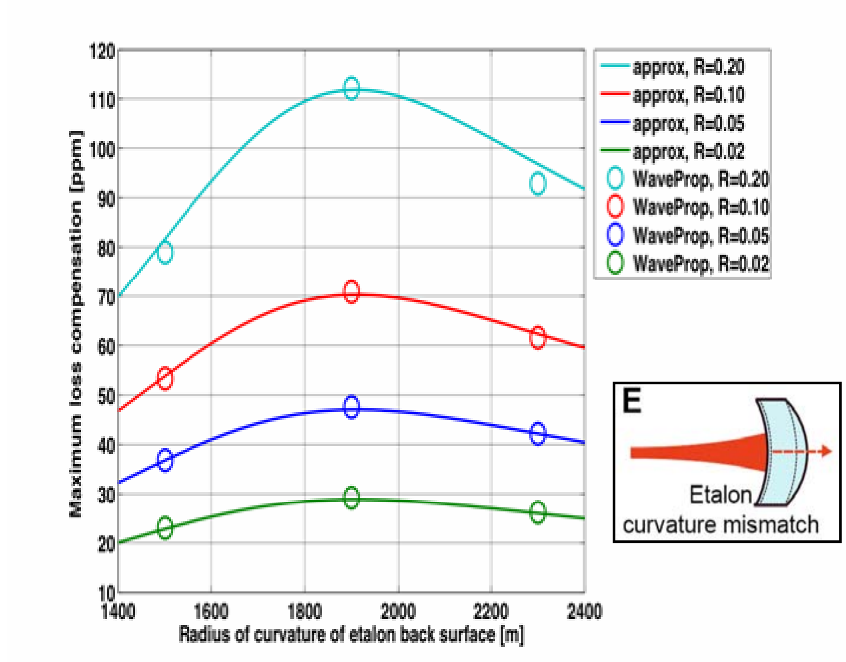
- For small misalignments the coupling coefficients k_{nmnm} can be approximated. The amount of light which remains in a TEM_{00} mode is given by:

$$k_{0000}(q,\gamma) = \exp\left(-\frac{\pi |q|^2 \sin^2(2\gamma)}{2\lambda\, \Im(q)}\right)$$

(q is the Gaussian beam parameter of the light at the mirror)

Tuning Range of imperfect Etalon

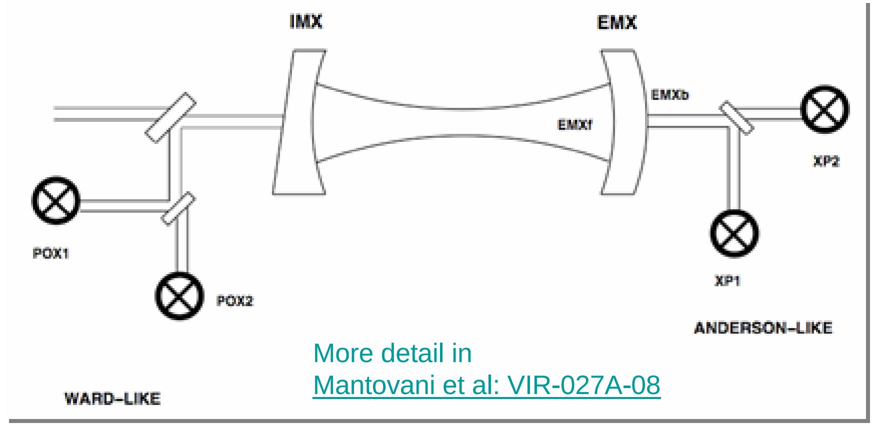


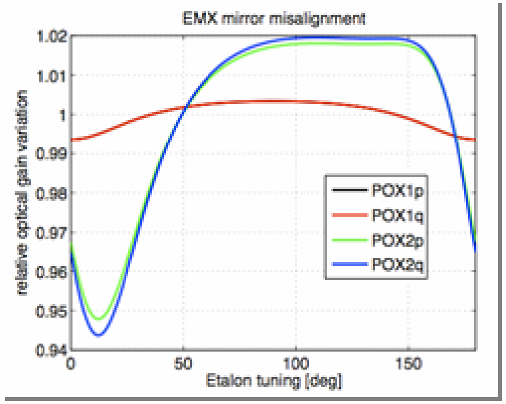


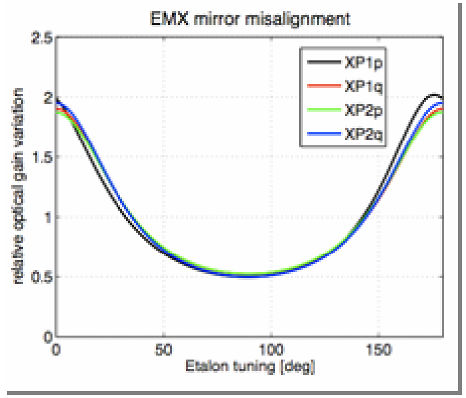
- Requirements for Etalon manufacturing accuracy:
  - Parallelism better than a few urad.
  - ROC deviation: uncritical

Influence of Etalon Tuning to other Subsystems: Example Alignment

- Evaluation of global alignment sensing and control.
- Simulated Ward-technique and Anderson-technique.
- For perfect etalon: No surprises.
- For non perfect etalon:
  - Coupling of etalon rear surface misalignment is 4 to 5 orders below etalon front surface misalignment.
  - Amount of first order optical modes inside the arm cavity origination from etalon imperfections is found to be negligible.







Summary

- Presented overview of how to choose the main characteristics of the Advanced Virgo arm cavity.

- More detailed analysis for wedges vs etalon:
  - Presented potential design (wedged ITM, etalon at ETM)
  - Presented requirements for:
    - Seismic isolation (wedge)
    - Temperature stability of etalan (optical phase noise)
    - Manufacturing accuracy of the etalon
  - Checked for negative implications of other subsystems:
    - Alignment sensing and control

- Publication on the arxiv:

  Hild et al: "Using the etalon effect for in-situ balancing of the Advanced Virgo arm cavities"
  arXiv:0807.2045

Thanks for the helpful input from the LSC review !