Advanced Virgo Beam Geometry

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Executive summary: Beam Geometry

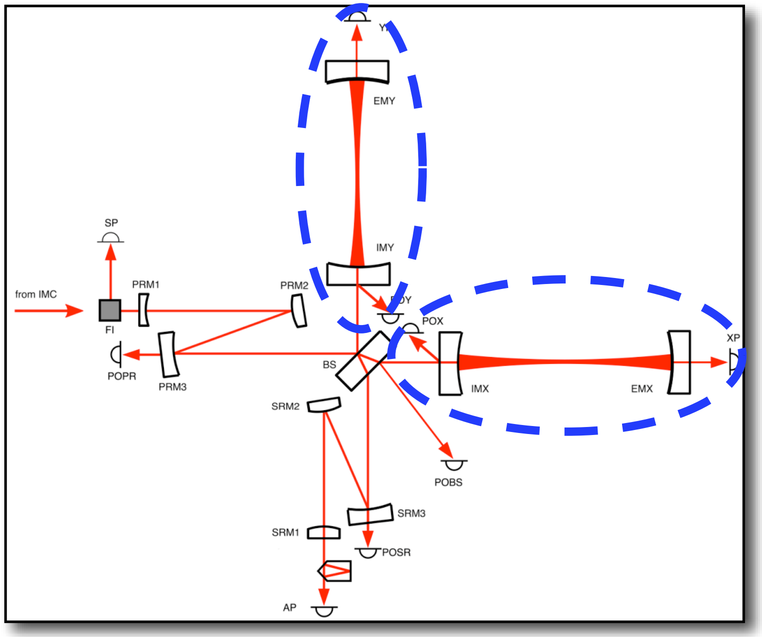
- Advanced Virgo needs to have a sensitivity competitive with Advanced LIGO in order to contribute to any network analysis.
- This requires very large beam sizes (close to instability).
- Trade off decision taking into account:
  - Sensitivity
  - Mode non-degeneracy
  - Mirror size / clipping losses
- The current design features:
  - Beam sizes of 5.5 cm (IM) and 6.5 cm (EM).
  - The corresponding ROCs are 2% off instability.
  - The resulting sensitivity is about 30% worse than Advanced LIGO.
- Proposal for small R&D experiment to test the feasibility of the beam geometry.

And now the details …

Arm Cavities: The Core of a GWD

- 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.



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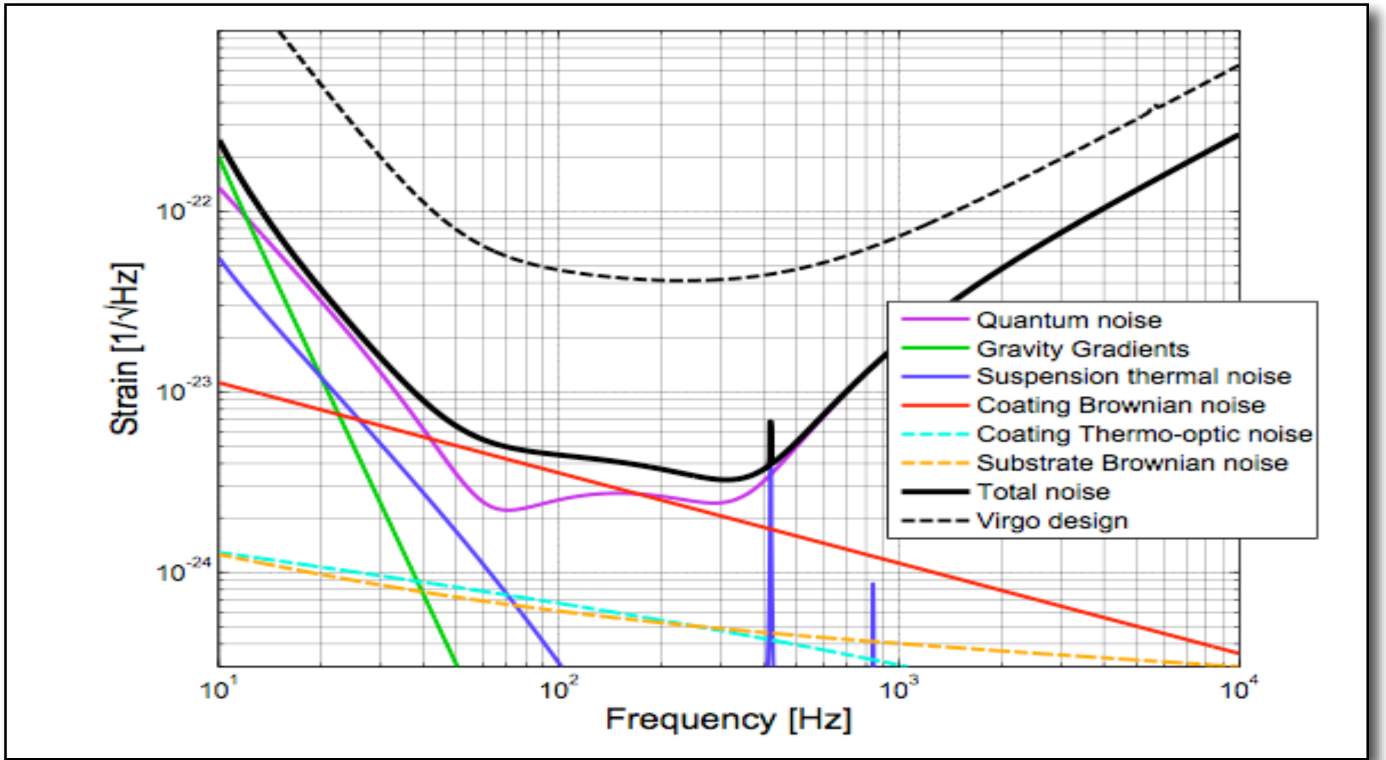
Arm cavities and Coating Brownian noise



- Coating Brownian noise is the limiting noise source in the mid frequency range.

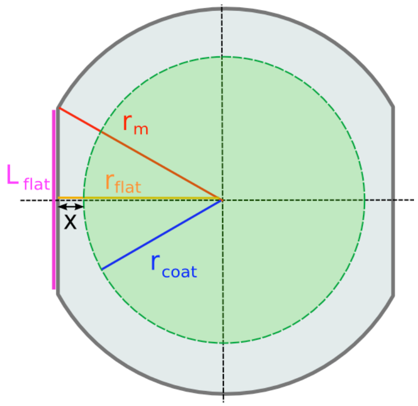
Beam Geometry

- 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

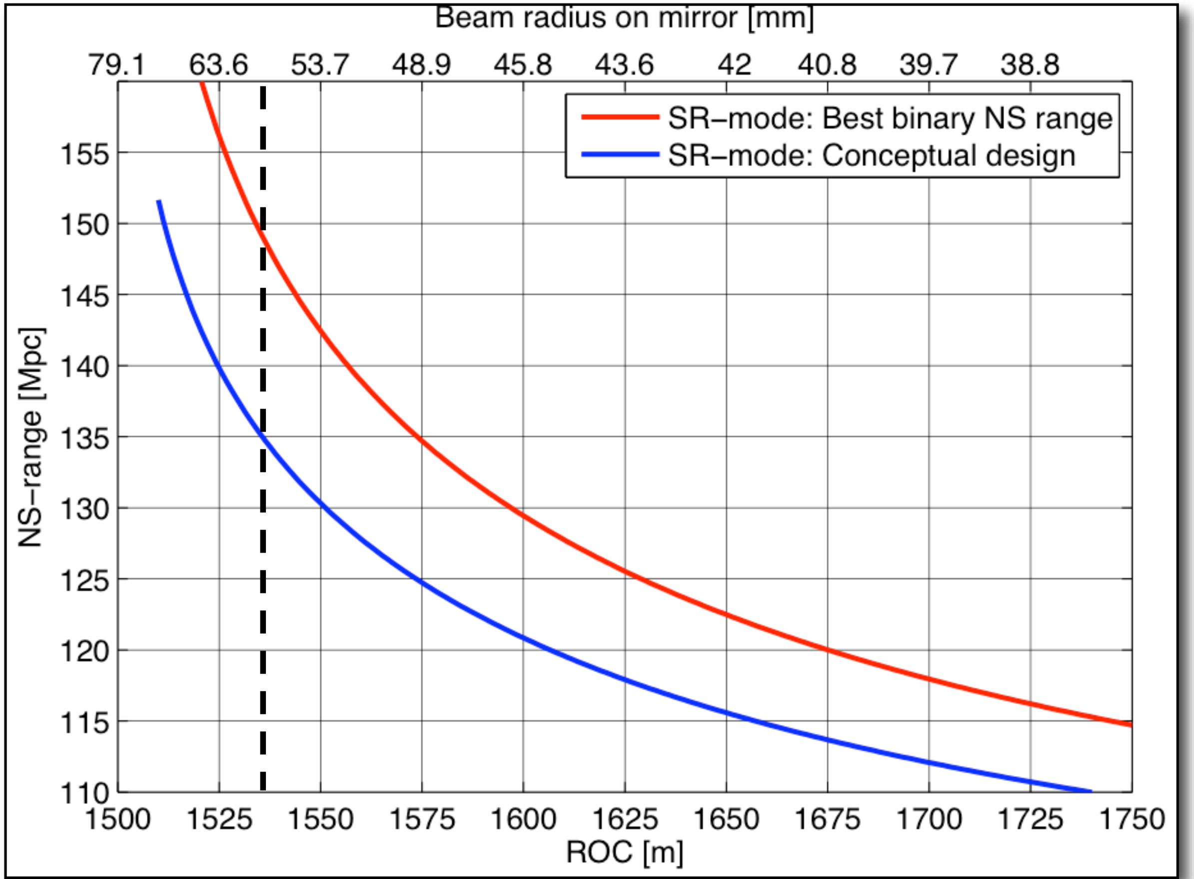
How to decide on Beam Size ?

- Sensitivity
  - Advanced Virgo needs to have a sensitivity pretty close to Advanced LIGO.
  - Need to make the beams as large as possible!
- Cavity stability
  - Large beams means pushing towards instability of the cavity.
  - Cavity degeneracy sets limit for maximal beam size
- Mirror size
  - The maximum coated area might also impose a limit for the beam size.
  - Clipping losses require coating size 5 times the beam radius.
  - Consider beam sizes of up to 6.5cm.



Sensitivity with symmetric ROCs

- With 6cm radius and 1530m ROC: Advanced Virgo obtains about 150 Mpc.
- For comaprison: Advanced LIGO will achieve a 180 to 200 Mpc.



Cavity Stability and Choice of ROCs

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

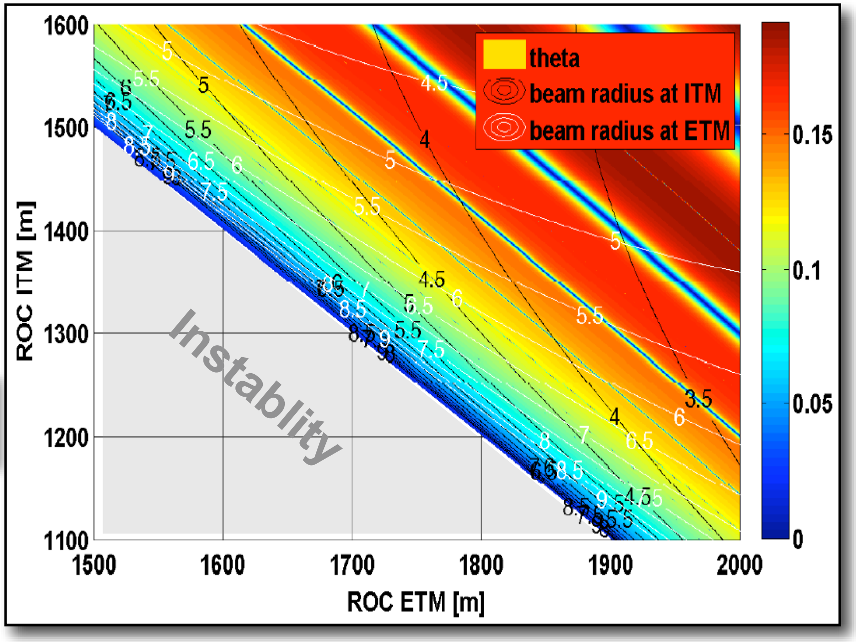
$$\phi_{l+m} = (l+m)\frac{1}{\pi}\arccos\sqrt{(1-\frac{L}{R_{c,i}})(1-\frac{L}{R_{c,e}})}.$$

  - 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:

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

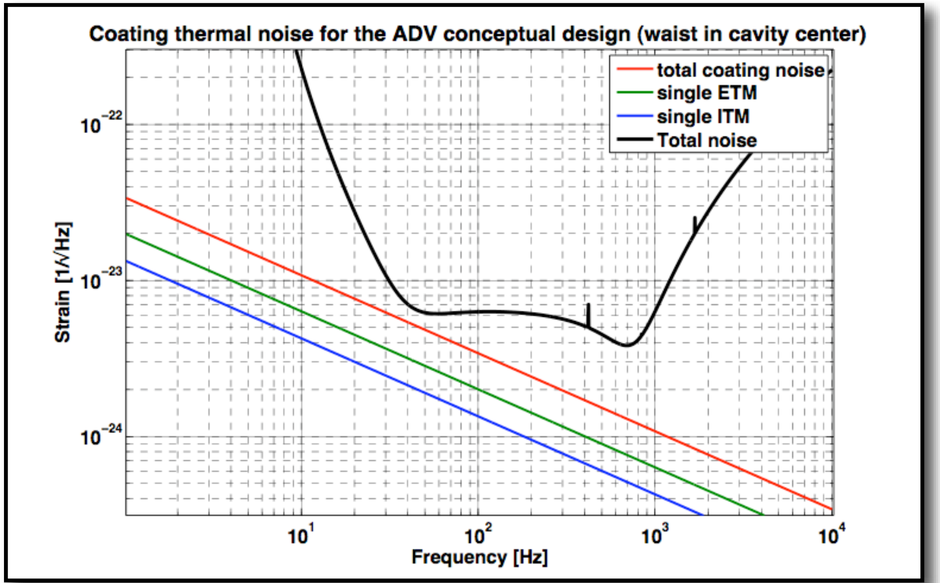


Beam Geometry

- 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)

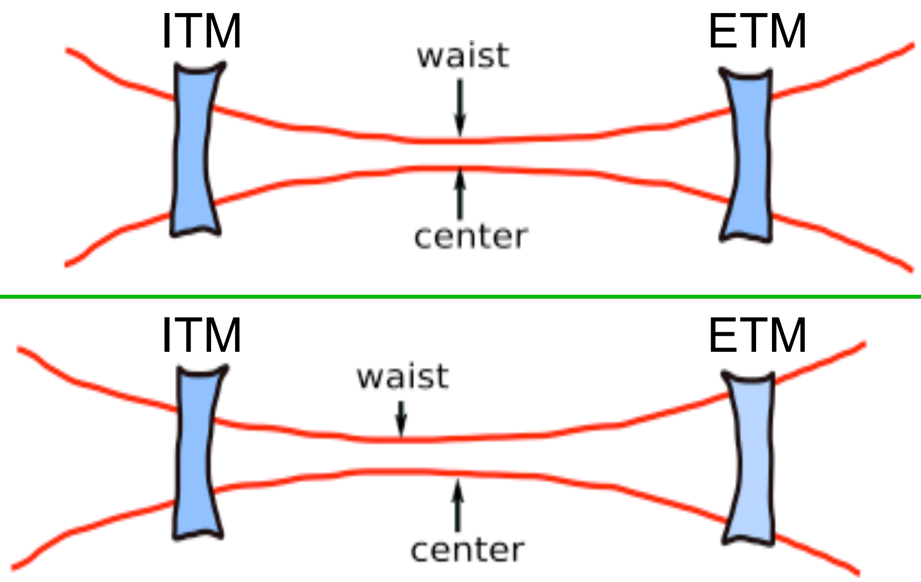


- For equal beam size ETM has higher noise.

Optimal Waist Position

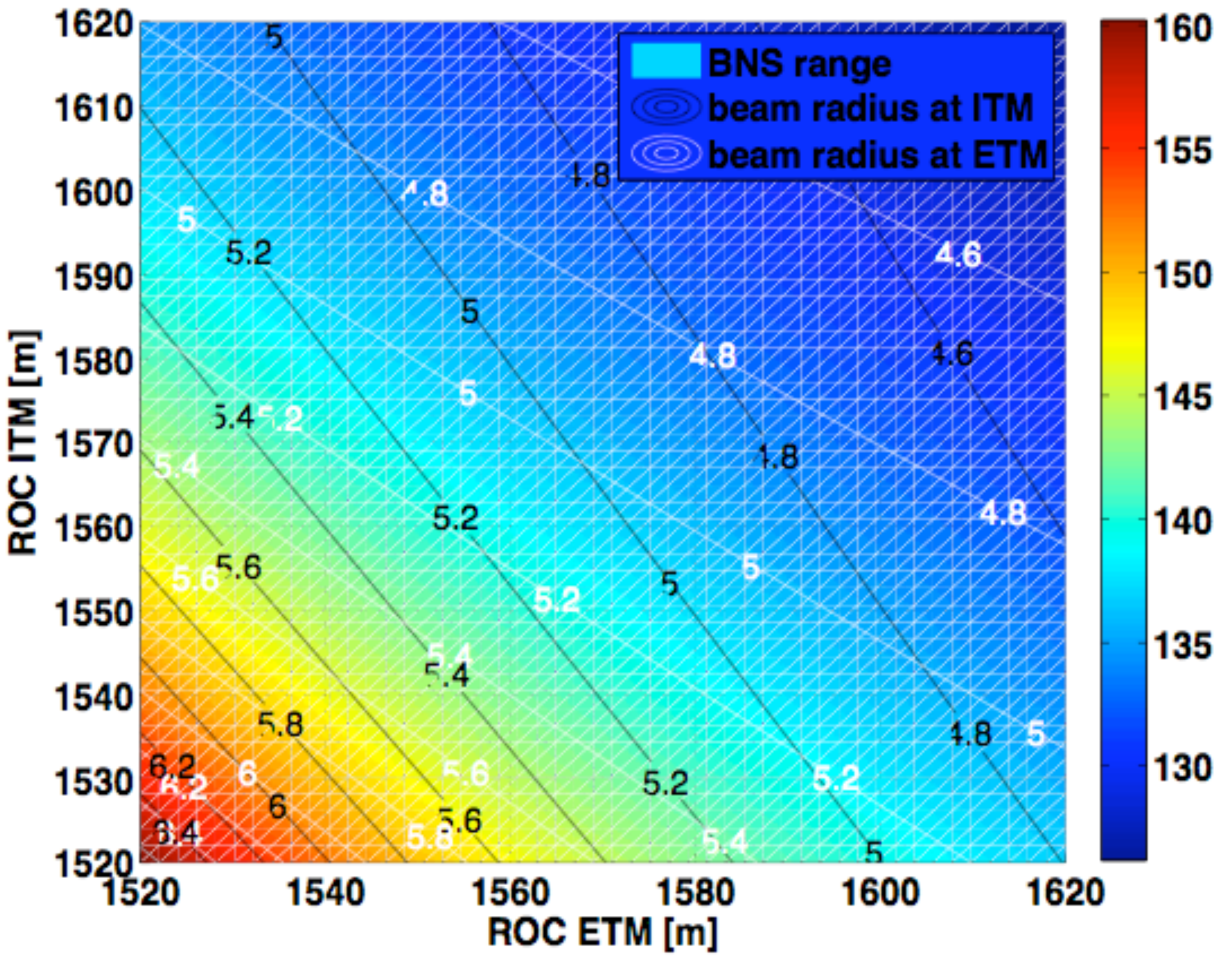
- In order to minimize the thermal noise we have to make the beam larger on ETM and smaller on ITM.
- Equivalent to moving the waist closer to ITM.
- Nice additional effect: the beam in the central area would be slightly smaller.

Symmetric ROCs = non optimal Coating noise



Asymmetric ROCs = optimal Coating noise

Beam Size


BNS range
beam radius at ITM
beam radius at ETM
ROC ITM [m]
ROC ETM [m]
1520
1530
1540
1550
1560
1570
1580
1590
1600
1610
1620
1540
1560
1580
1600
1620
160
155
150
145
140
135
130

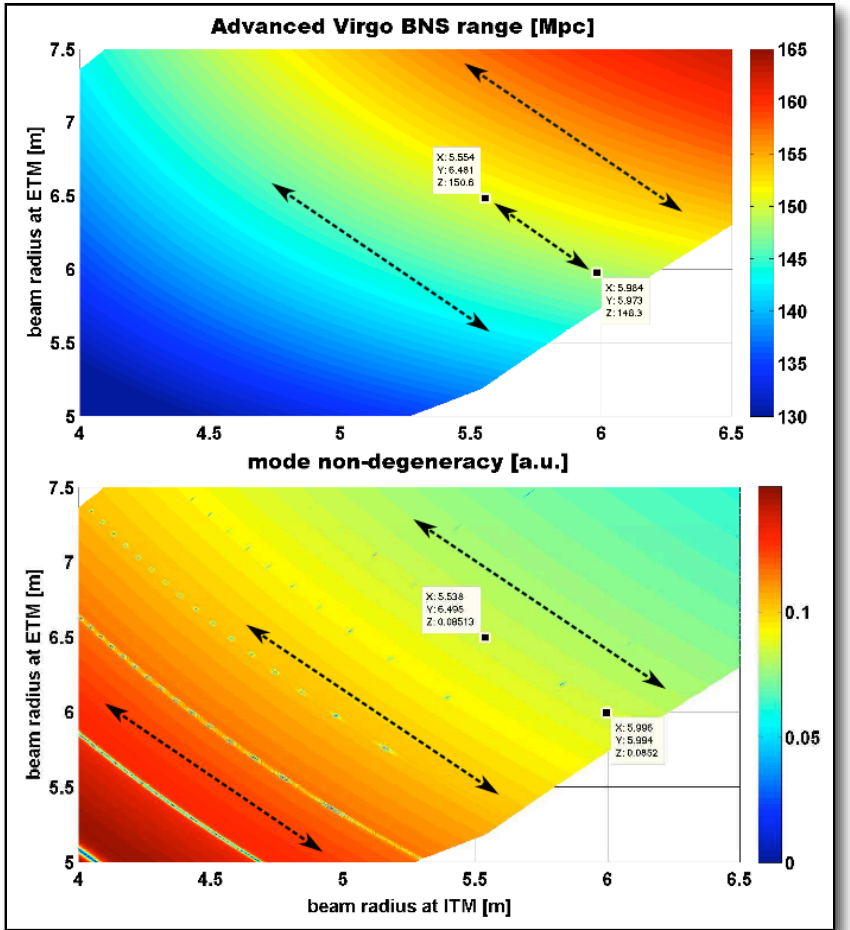
Choice of ROCs/beam size: Sensitivity vs Mode-non-degeneracy

- In general mode-non-degeneracy and sensitivity go opposite.

- Asymmetric ROCs are beneficial:
  - For identical mode-non-degeneracy (parallel to arrows in lower plot) and even slightly increased senstivity we can reduce the beam size in the CITF from 6 to 5.5 cm.

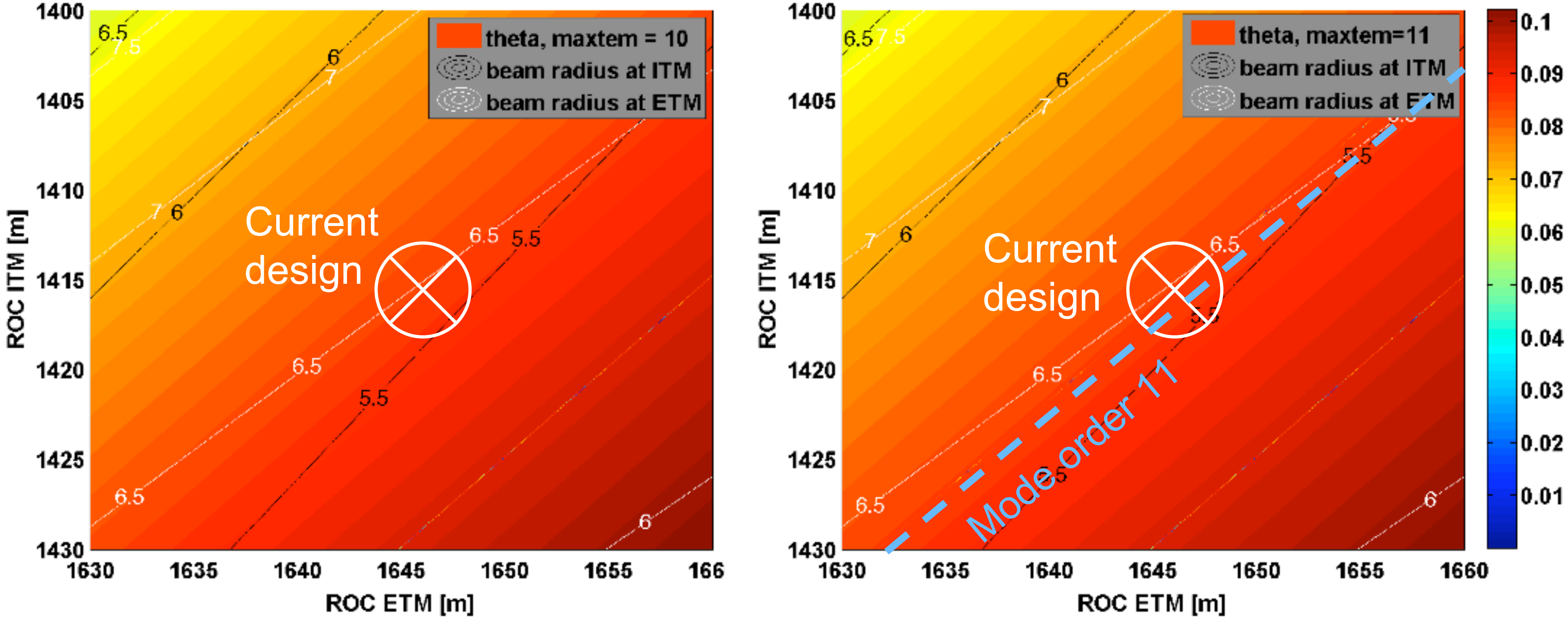
	input mirror	end mirror
beam radius [mm]	56	65
ROC [m]	1416	1646

Table 8: Design parameter of the AdV arm cavity geometry.



And even a bit more details …

Determining the closest higher order mode of the proposed geometry

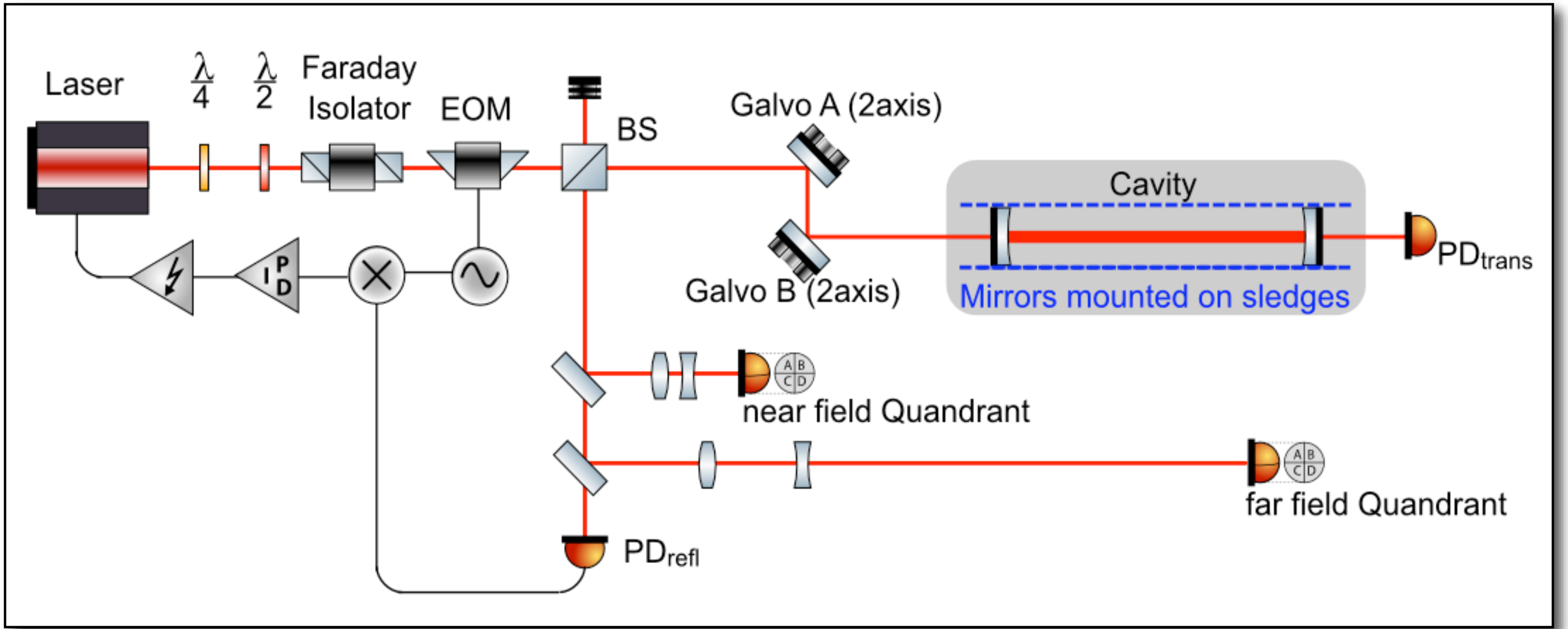


- The higher order mode closest to being resonant in the arm cavities is of the order 11.

Proposal for a small R&D project

- The final choice of mirror ROCs needs to be taken only when the substrates are send for polishing => gives us some spare time for tests.
- Propose that one of the Virgo labs conducts the following experiment:
  - Get two small mirrors (1 or 2”):
    - High quality polishing + corrective coating (LMA)
    - Aim for ROC of 52cm.
  - Set up a non-suspended cavity of 100cm length
    - Mirrors are mounted on tracks and can be moved forth and back on mm/cm scale.
  - Make use of an auto-alignment system to ensure sufficient suppression of alignment effects.
  - Perform measurements of the cavity finesse to determine the actual losses of the cavity.
- The result of these measurements can then be compared to FFT simulations using the actual mirror maps.

Sketch of potential experimental setup



- Servo loops for the differential wavefront sensing and control are omitted for clarity…

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