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Estimation of astigmatism losses in the Advanced Virgo non-degenerate recycling cavities

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Introduction

In this document we present a preliminary estimation of the losses induced by astigmatism in the advanced Virgo non-degenerate recycling cavities (NDRCs) [1], for each of the four scenarios discussed whitin the OSD group [2]. After a presentation the of the method and the approximations we used, the results are presented.

Method and approximations

The estimation of the losses is similar to the one described in [3].

The recycling cavity is simulated through a set of ABCD matrices for ray-matrix propagation, for both the tangential and sagittal planes [4]. Only one arm of the recycling cavity is simulated, in each simulation run.

The sagittal and tangential eigenmodes of NDRCs are found by solving the autoconsistency equation q=(Aq+B)/(Cq+D), where the ABCD are the coefficent of the tangential and sagittal matrices for a roundtrip propagation inside the recycling cavity.

The astigmatism will affect the coupling between the input (output) beam and the power (signal) recycling cavity, and between the recycling cavity and the Fabry-Perot cavities.

In order to estimate the coupling we compute the overlap integral, defined as the scalar product between the gaussian fields $\psi_1(R_{x1},R_{y1},w_{x1},w_{y1})$ and $\psi_2(R_{x2},R_{y2},w_{x2},w_{y2})$.

$$P = \iint \psi_1(R_{1x},R_{1y},w_{1x},w_{1y})\psi^*{}_2(R_{1x},R_{1y},w_{1x},w_{1y})dxdy$$

The coupling losses are given by:

$$L = 1 - P^2$$

We have checked that the overlap integral gives the simple coupling coefficients $\Delta w/w$ for a waist size defect, and $\lambda b/2\pi w^2$ for a waist displacement;, here, Δw is the difference in waist size and b is the difference in waist position [5].

Input beam coupling

The input beam (which is a free parameter) can be chosen to match the sagittal plane or to match an average value between the sagittal and the tangential corresponding values.

Fabry-Perot cavity coupling

The coupling between the FP and recycling cavity is computed considering the two cavities as perfectly decoupled.

The coupling between the FP cavity and the recycling cavity is computed considering an artificial perfect sagittal matching or considering the nominal recycling and FP cavity parameters. In the first case we decouple the astigmatism effects from a possible sub-optimal matching between the two cavities.

Comparison with advLIGO

In order to check our results, we have simulated the advLIGO configuration, as reported in [3] and [6].

In the LIGO work, a sagittal matching is supposed for both the input beam and the FP. For the nominal parameters given in [3] we find total losses of 1.68%, compatible with the one found by LIGO simulation (1.5%). We also find that the stability range of the recycling cavity is compatible to the one showed in [6] (+/- 0.2% in the PRM3 ROC).

Results and interpretation

For each scenario a plot of the losses versus the variation of PRM3 and PRM2 is shown. For all the scenario the color plot is first given in a range of ROC variation of 1%, in order to appreciate the differences in the tolerances between different scenarios. The instability regions are in white.

Scenario 1

The tilt angles are 2.5 (PRM3) and 3.5 (PRM2) degres. For the nominal parameters and a tilt of the lenses of 1 degree the total losses are about 1% for the X arm (fig.1), but the Y arm is unstable. Changing PRM3 from 33.0 m to 33.3 m both X and Y are stable (fig.2 for the X arm) and we have:

input(average) + arm losses : 1.9% (X) 1.6 (Y)
input(average) + arm(sag-match) losses : 0.02% (X) 1.9% (Y)

Scenario 2

With tilt angles of 3.3 degrees for PRM3 and PRM2 and the nominal parameters the 2 planes are not stable at the same time (even if a set of parameters which gives a simoultaneous stability maybe exists) (fig.3). For the simulations we use the angle used by Julien Marque for the OptoCad simulation, 1.7 degrees for both PRM3 and PRM2. Changing the PRM3 (from 12.55 m to 12.56 m) and lprm1 (from 10.5 to 10.85 m) we have (fig.4):

input(average) + arm losses : 7%
input(average) + arm(sag-match) losses : 5.6%

No significant difference is found between X and Y arm.

Scenario 3

The tilt angles are 1.9 degrees. With the nominal parameters the cavity is unstable (fig.5). Changing R1 from 4.78 m to 3.9 m and R3 from 27.0 to 27.07 m we have (fig.6):

input(average) + arm losses : 2.6%
input(average) + arm(sag-match) losses : 2%

No significant difference is found between X and Y arm.

Scenario 4

The tilt angles are 1.9 degrees. With the nominal parameters the cavity is almost unstable (fig.7) Changing PRM2 from 4.53 m to 4.35 m and PRM3 from 27.50 to 27.40 we have (fig.8):

input(average) + arm losses : 5%
input(average) + arm(sag-match) losses : 1.7 %

No significant difference is found between X and Y arm.

References

[1] Advanced Virgo team, *Advanced Virgo Preliminary Design*, Virgo internal note VIR-089A-08
[2] Freise A. & al. , *Advanced Virgo design: layouts for non-degenerate recycling cavities,* OSD internal note
[3] Arain M. A. , *Analysis of Mode Mismatch due to Astigmatism at Recycling Cavity Mirrors,* LIGO internal note T080315-00-Z
[4] Massey G. A. , Siegman A. E. , *Reflection and Refraction of Gaussian Light Beams at Tilted Ellipsoidal Surfaces*, Appl. Opt. Vol. 8 n. 5, p. 975, 1969
[5] Anderson D. , *Alignment of resonant optical cavities*, Appl. Opt. Vol. 23 n. 17, 1984
[6] Arain M. A. , Mueller G. , *Design of the Advanced LIGO Recycling Cavities,* LIGO internal note P080004-00-Z

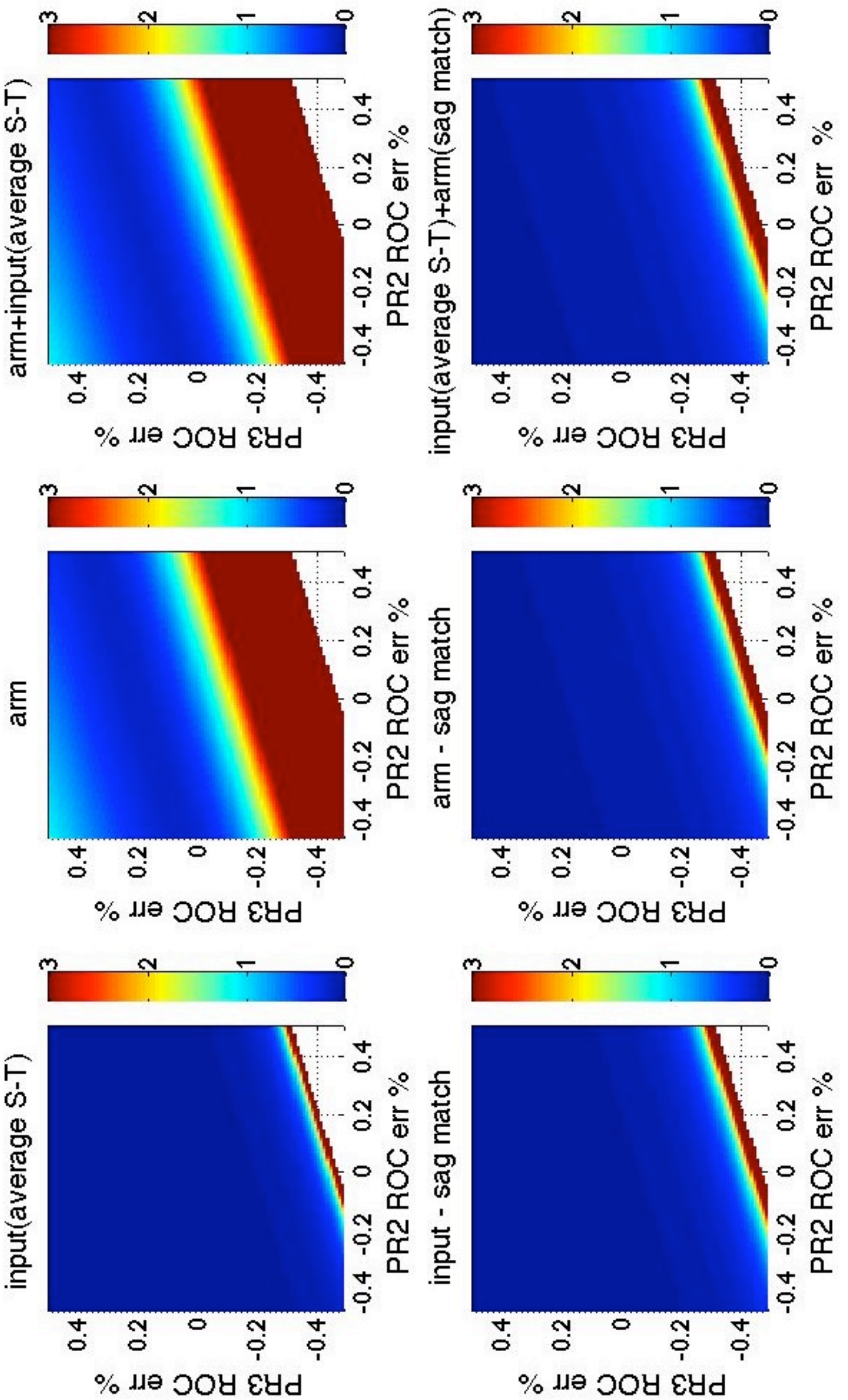

Fig. 1 : scenario 1, X arm, nominal parameters

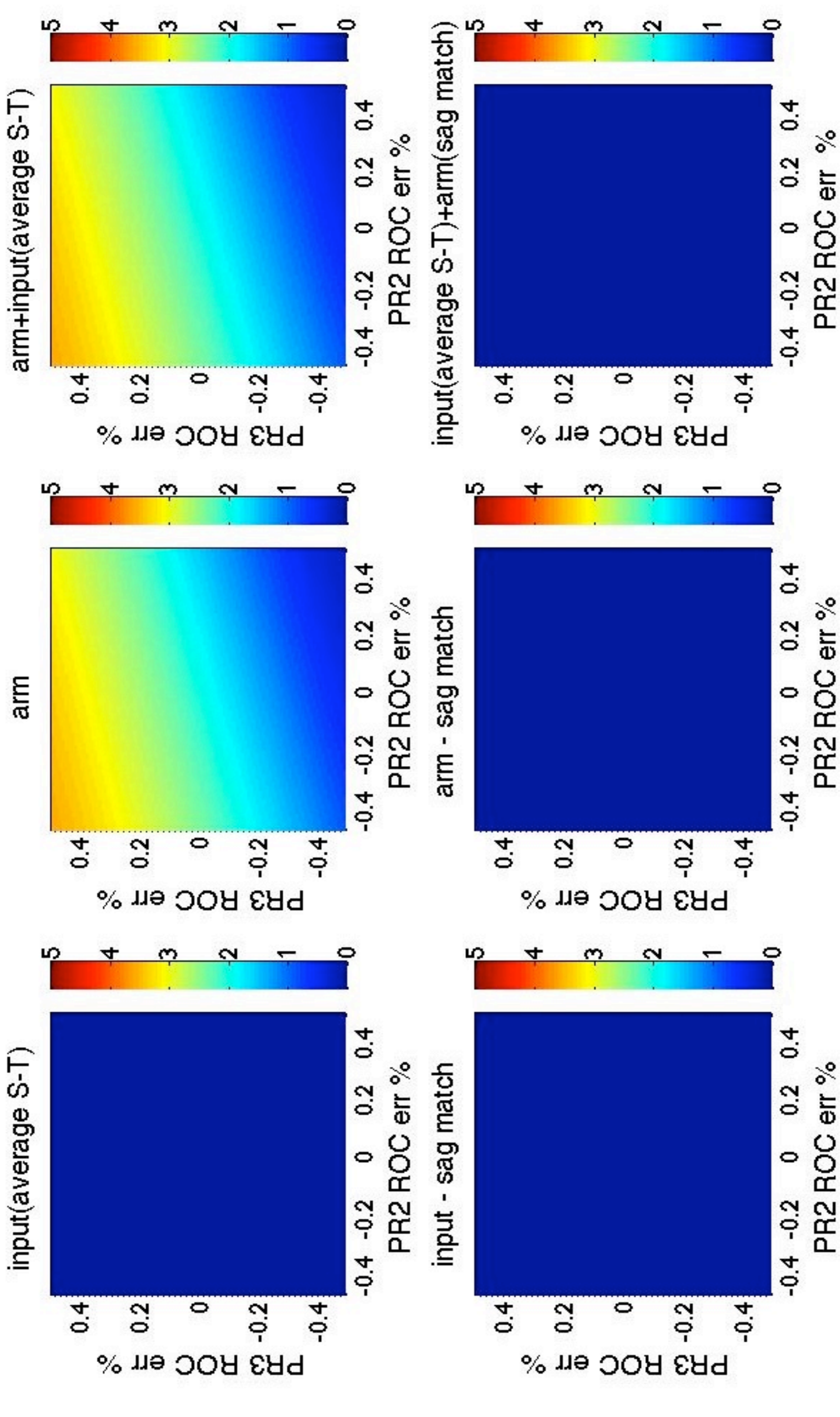

Fig. 2 : scenario 1 optimized, X arm

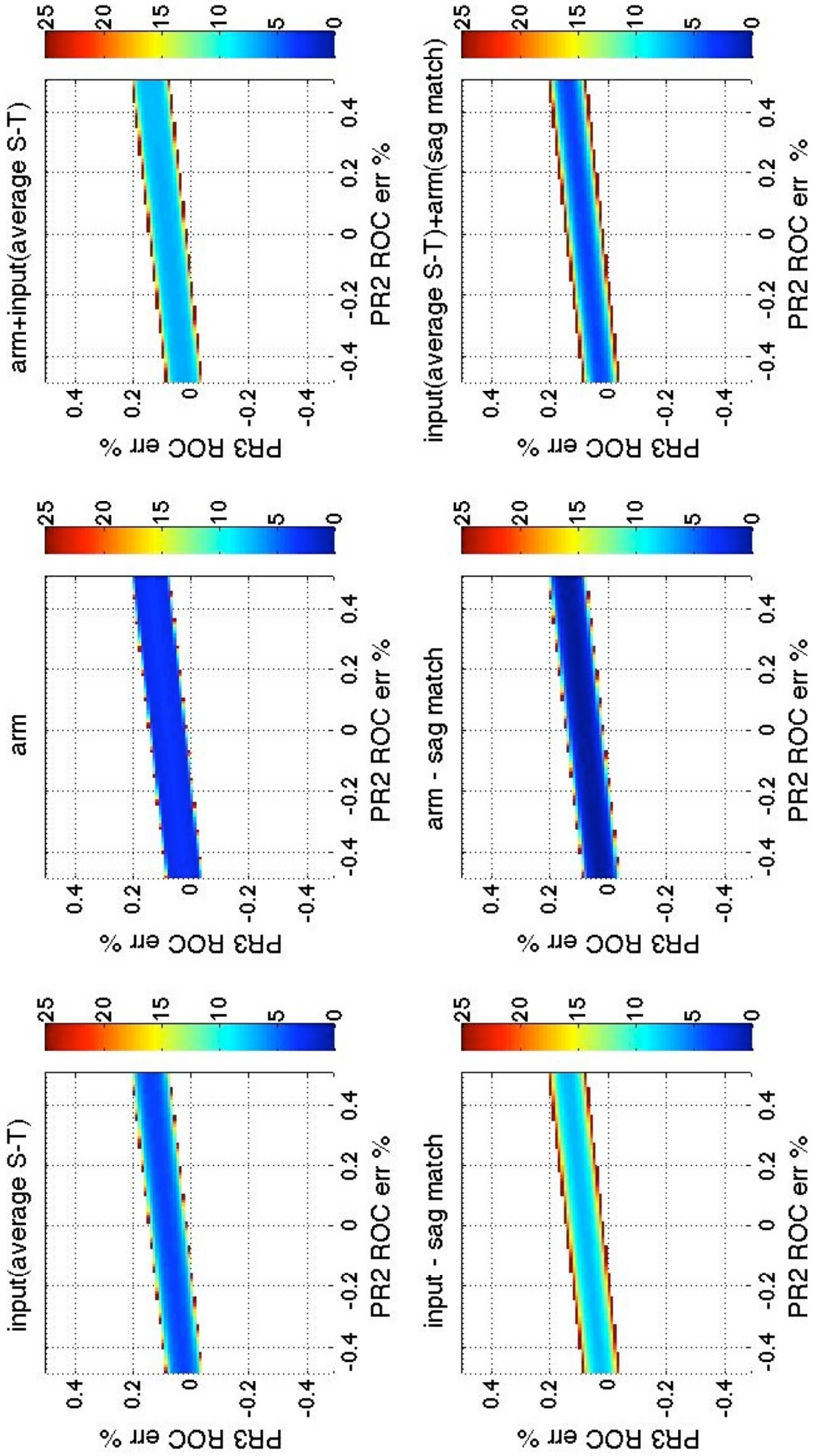

Fig. 3 : Scenario 2, nominal parameters

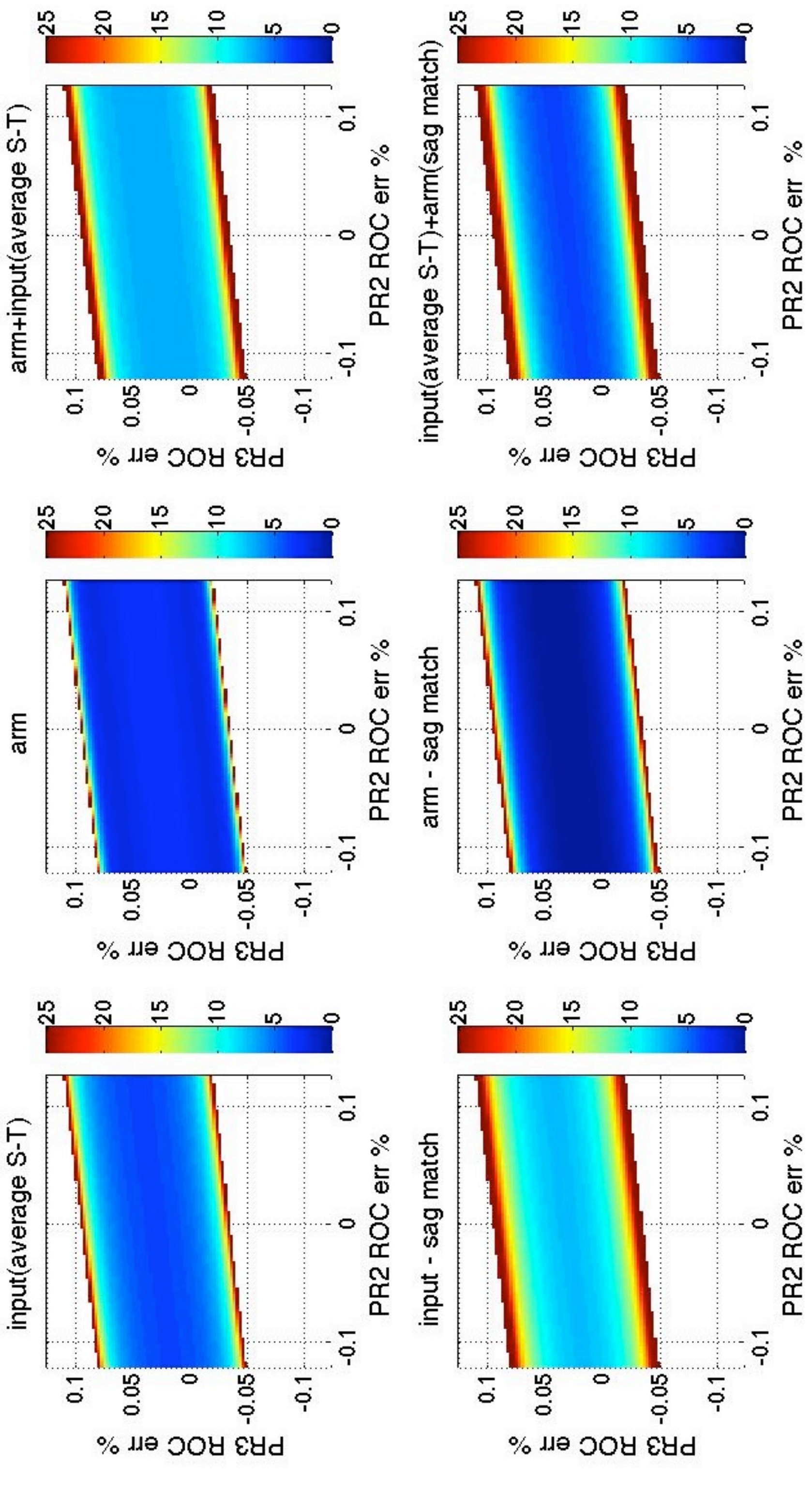

Fig. 4 : Scenario 2 optimized

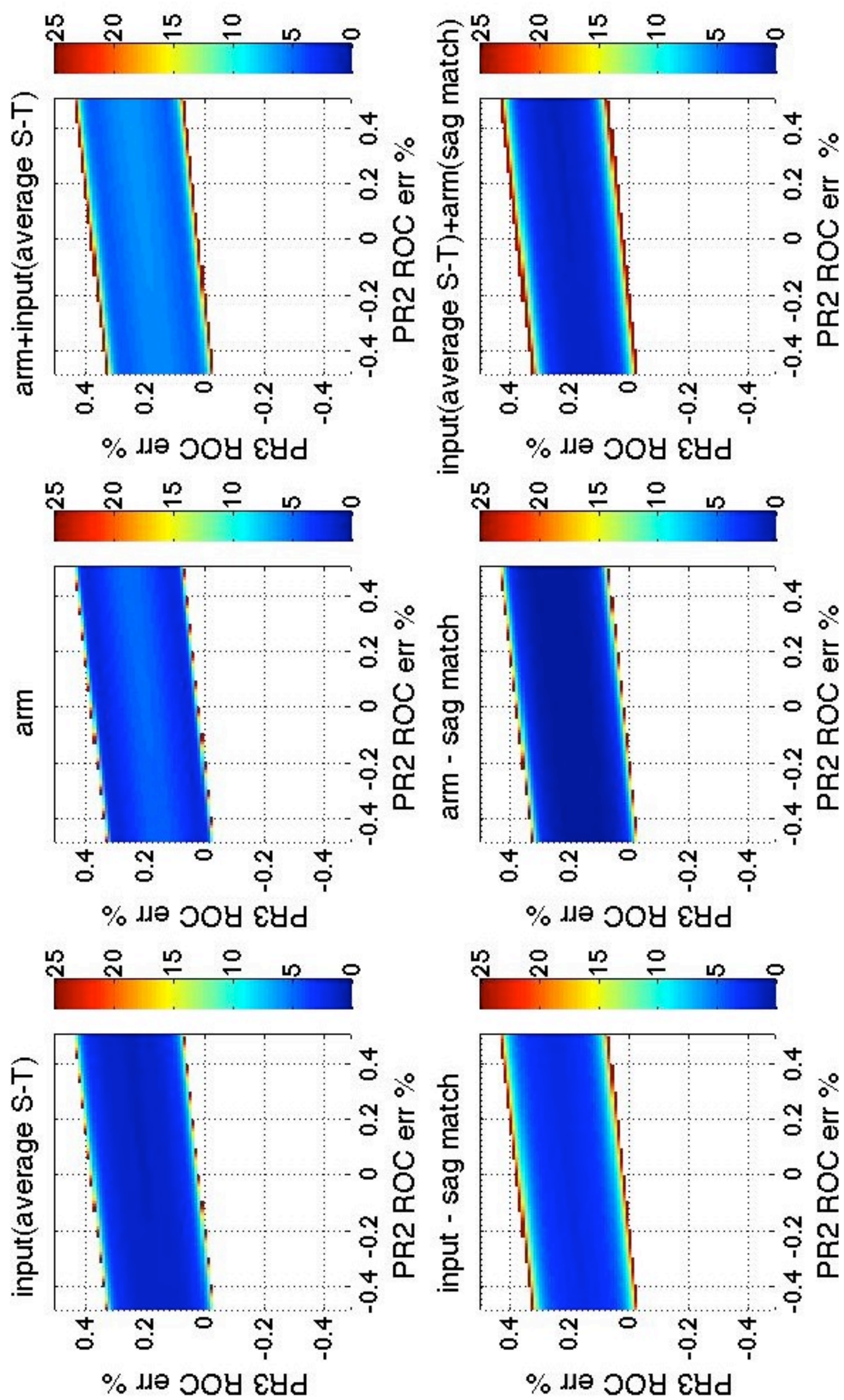

Fig. 5 : Scenario 3, nominal parameters

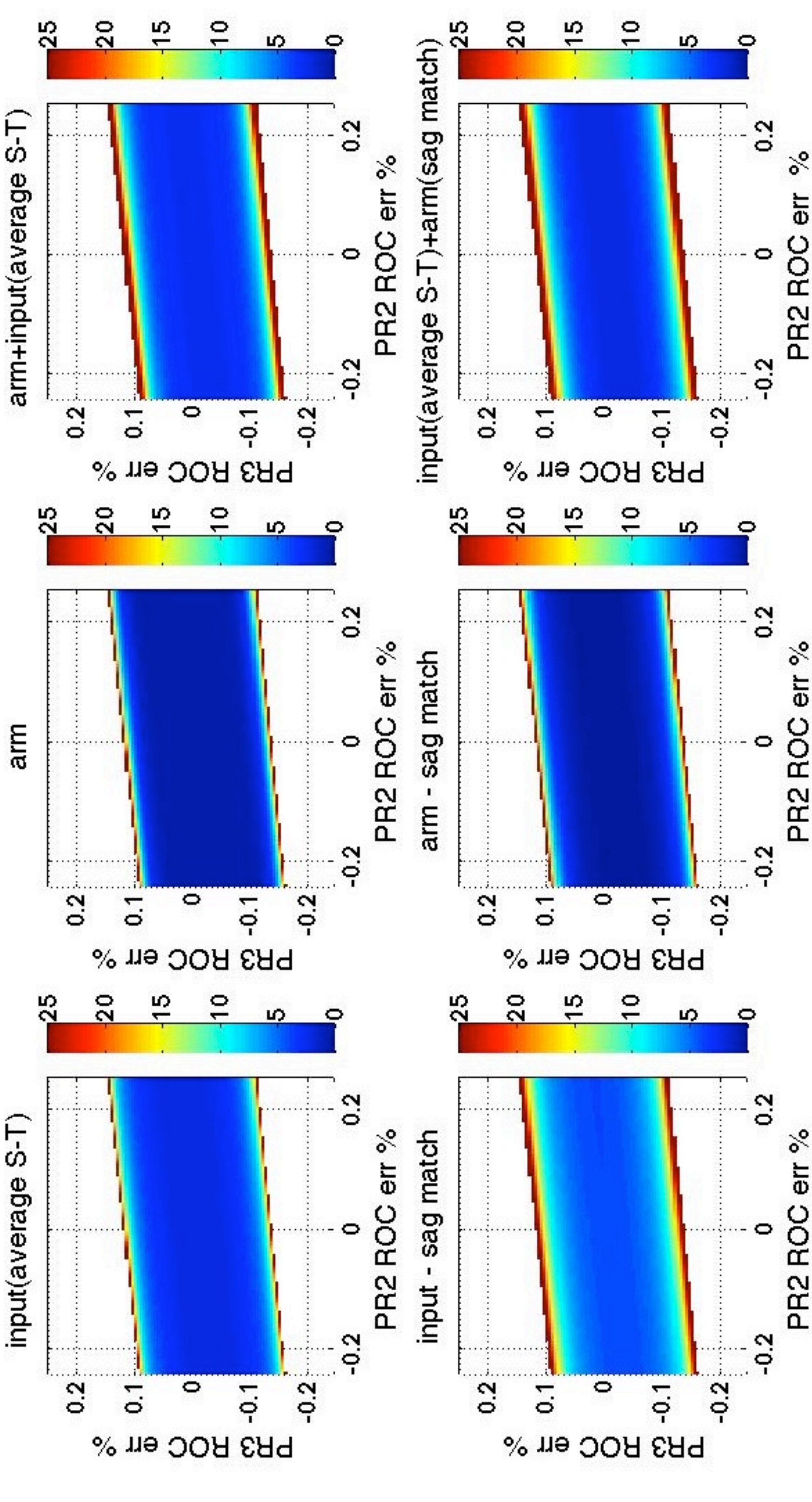

Fig. 6 : Scenario 3 optimized

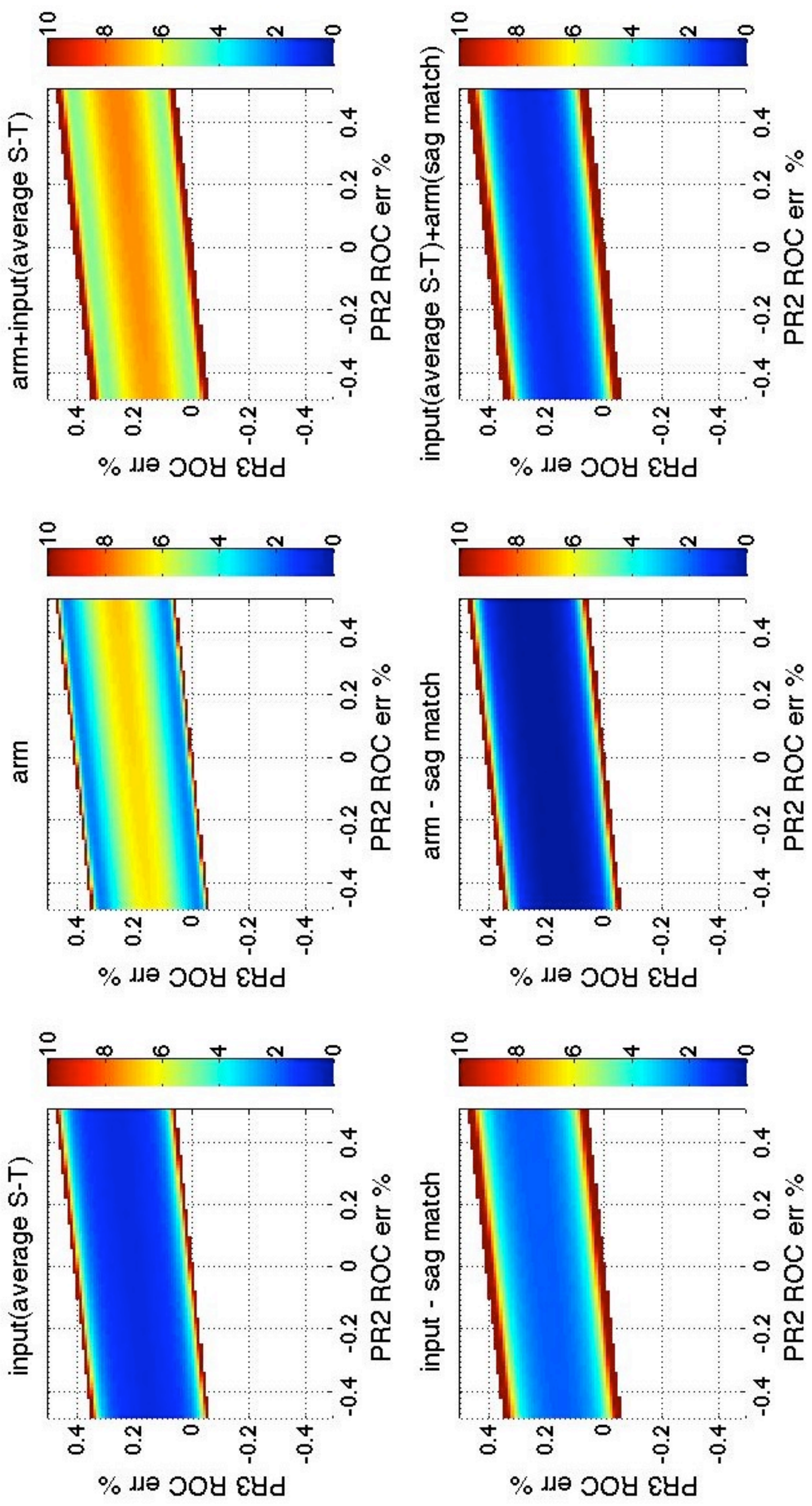

Fig. 7 : scenario 4, nominal parameters

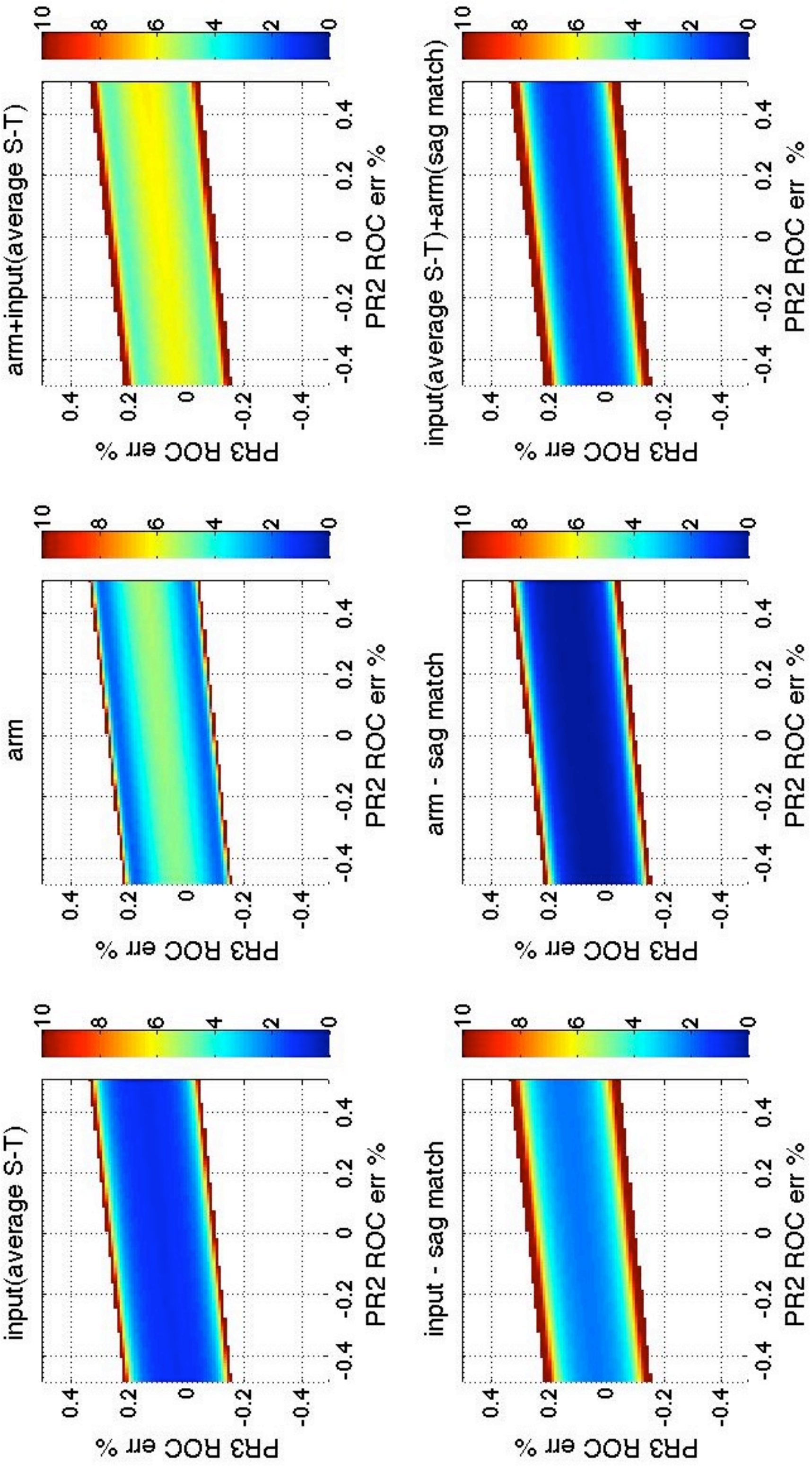

Fig. 8 : scenario 4, optimized

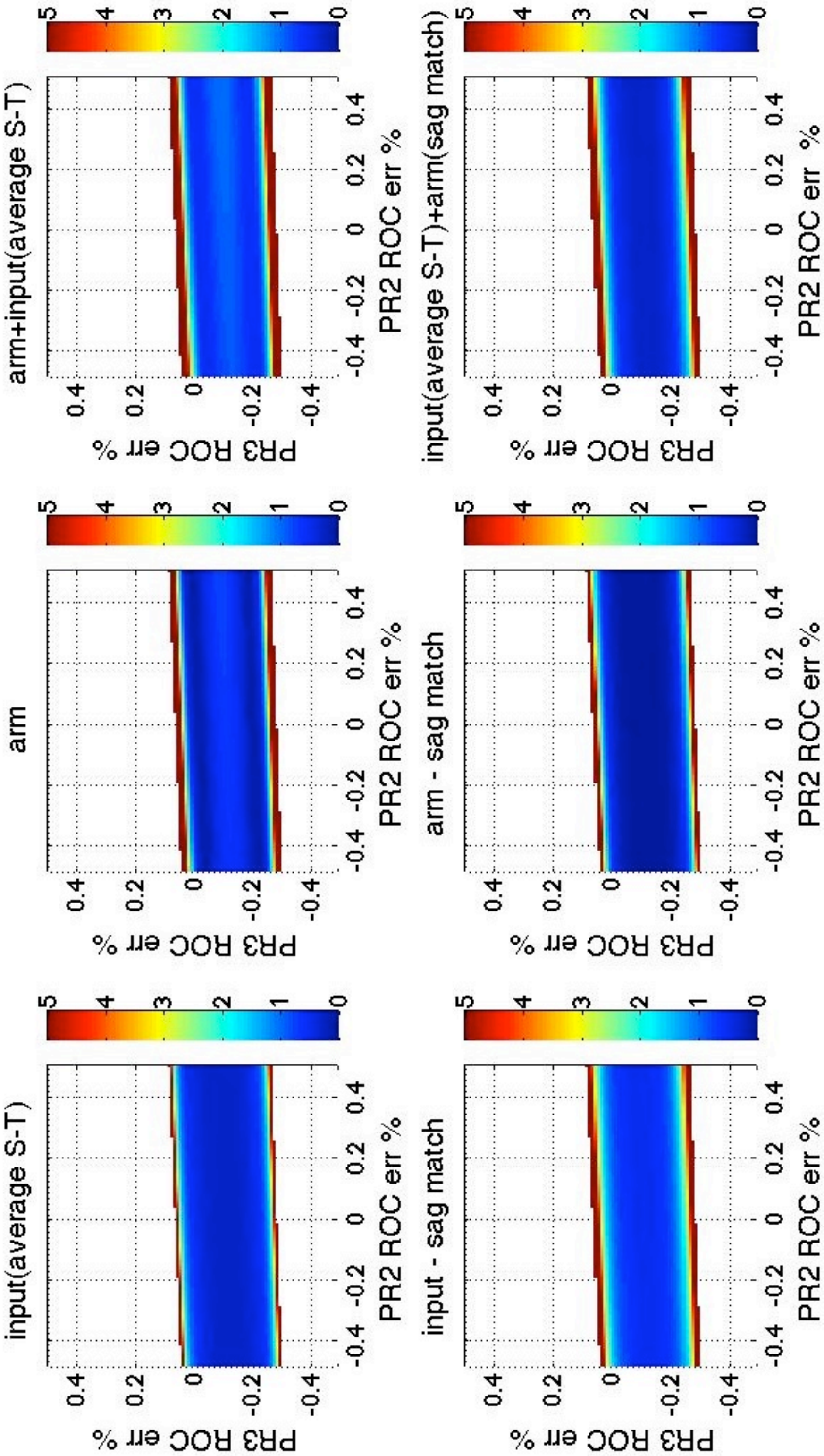

Fig. 9 : advanced LIGO