Low-losses stable recycling cavities for Advanced Virgo+ gravitational waves detector

Ward Amar – First year PhD seminar

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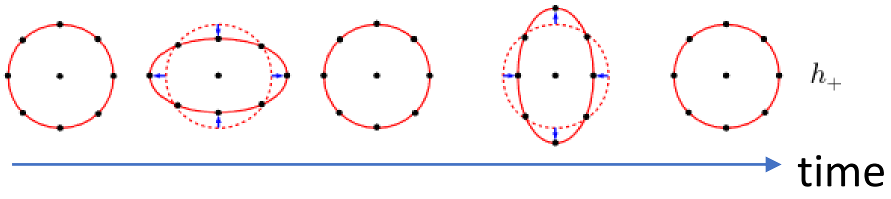
Content

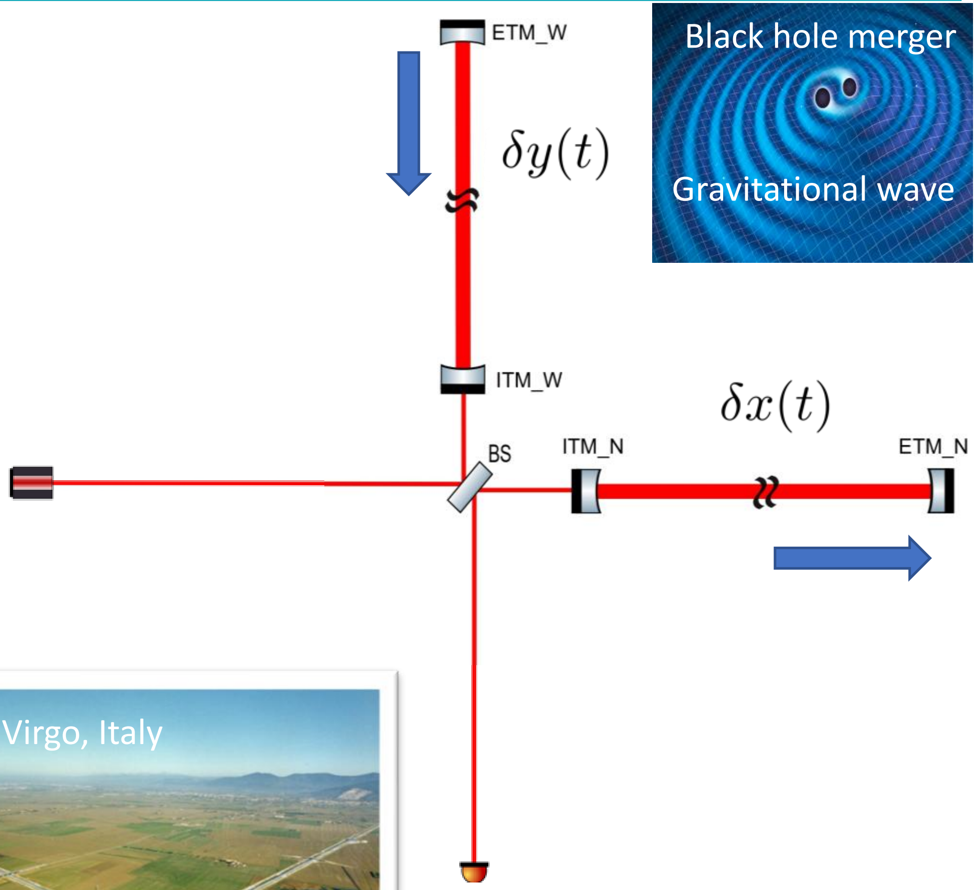
- The concept of gravitational waves detection
- Virgo gravitational waves detector
- Upgrade of Advanced Virgo optical design
- Research and development of the design of the stable recycling cavities.
- Summary and Future work

Detection concept of Gravitational waves

- Gravitational waves are ripples of the space-time caused by powerful astrophysical events.



- The design of the detector is a Michelson interferometer.
- When the GW passes through the detector it modifies the distances between the mirrors.
- This modification in length of the arms changes the power on the photodiode.
- There are three operational GW detectors, the two LIGO in the US and Virgo in Italy

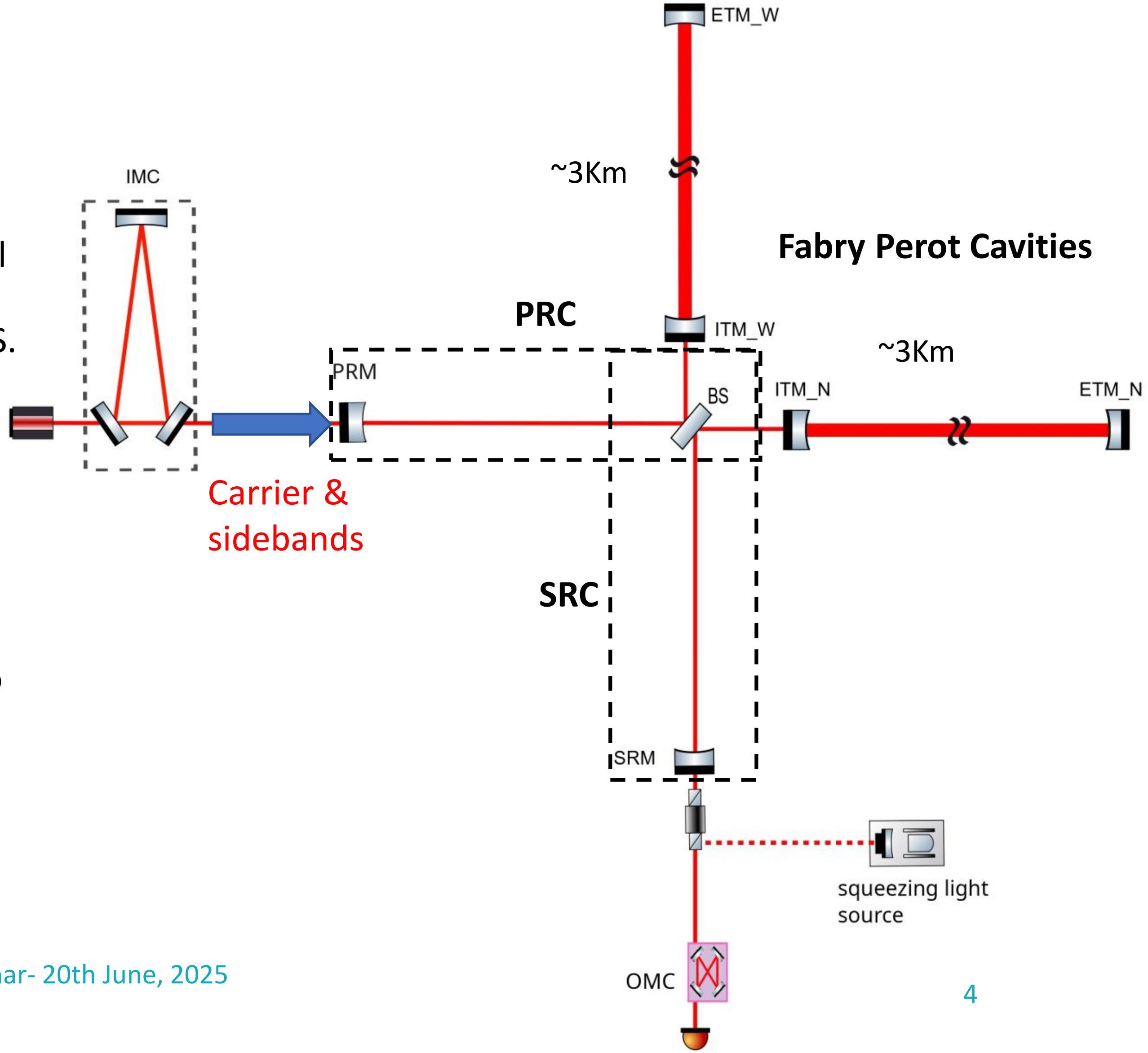


Design of Virgo gravitational waves detector

- The detection requires measuring tiny changes of distance ($\Delta L \sim 10^{-18}$m).

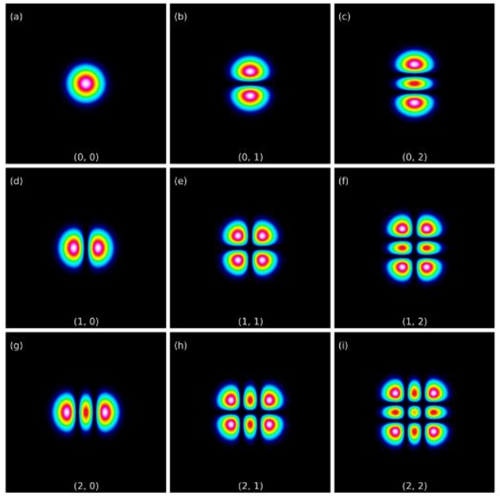
- The detector design:
  - **Fabry-Perot cavities**: amplifies the beam power and optical path.
  - **Power recycling cavity (PRC)**: increase the power at the BS.
  - **Signal recycling cavity (SRC)**: increase the detection bandwidth.
  - **Squeezing system**: responsible to decrease the quantum noise by injecting 'squeezed vacuum states'.

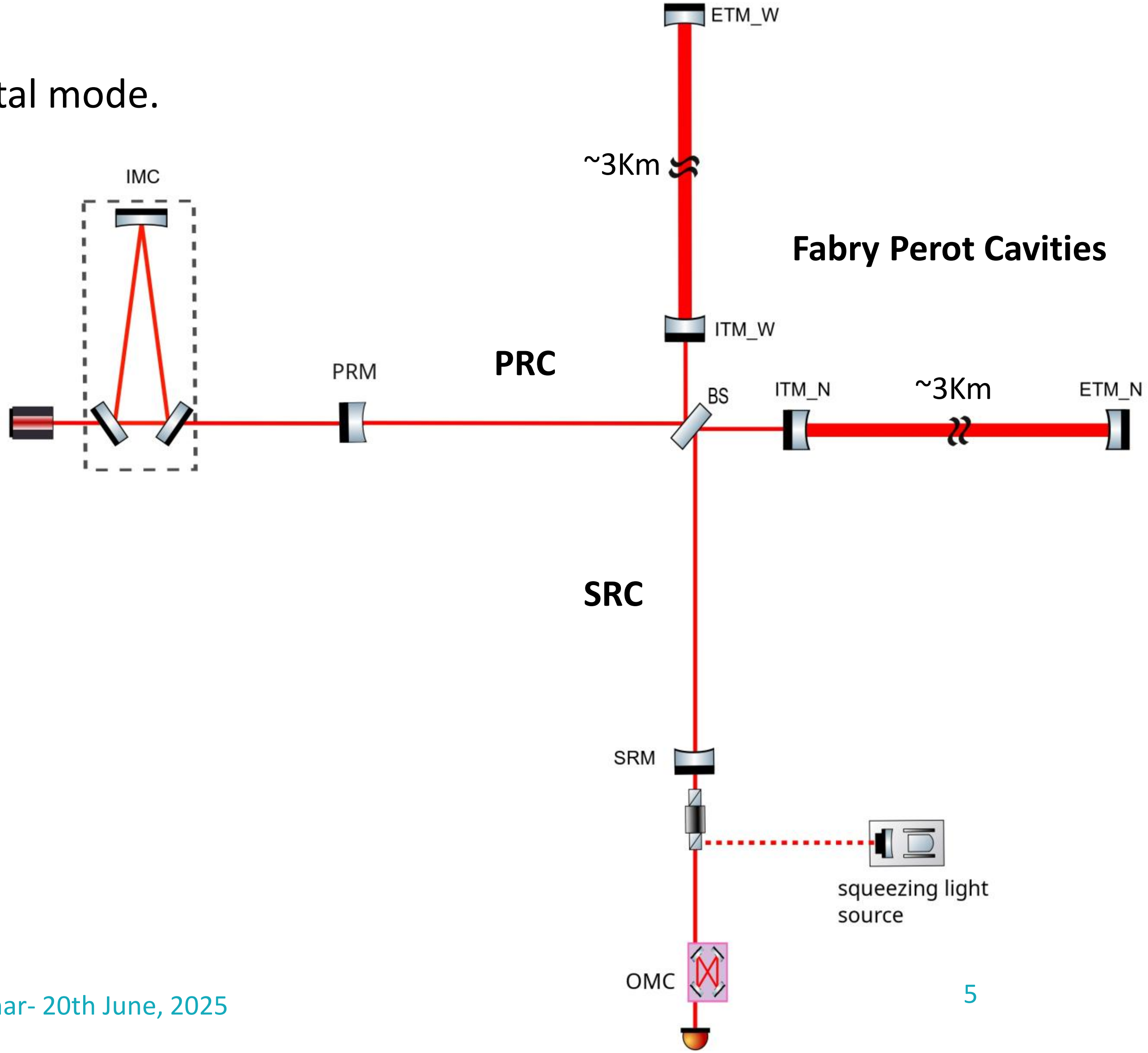
- Laser beam is phase modulated
  - **Modulation sidebands at frequency**: 6MHz and 54MHz. To provide error signal that helps control and align the interferometer.
  - Modulation sidebands have to resonate in the recycling cavities.



Design of Virgo gravitational waves detector: Disadvantages

- Degenerate recycling cavities
  - High-order modes co-resonate with the fundamental mode.
  - Amplifies the effect of the mirrors imperfections.
  - Creates beam aberrations.



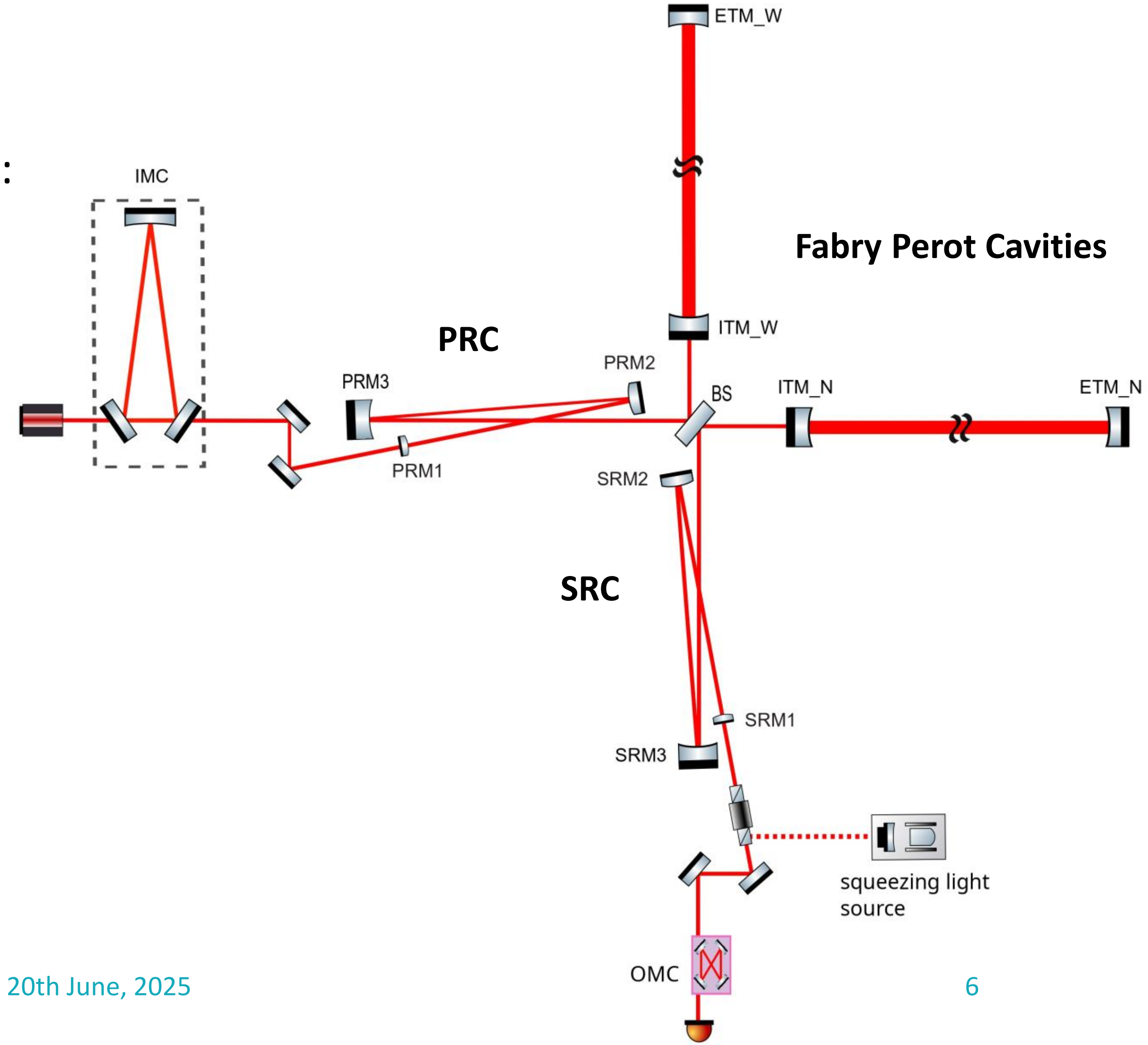


- **Consequences:**
  - →**Difficulty to control the detector.**
  - →**Larger optical losses.**
  - →**Increase the noise.**

Upgrade of Advanced Virgo+

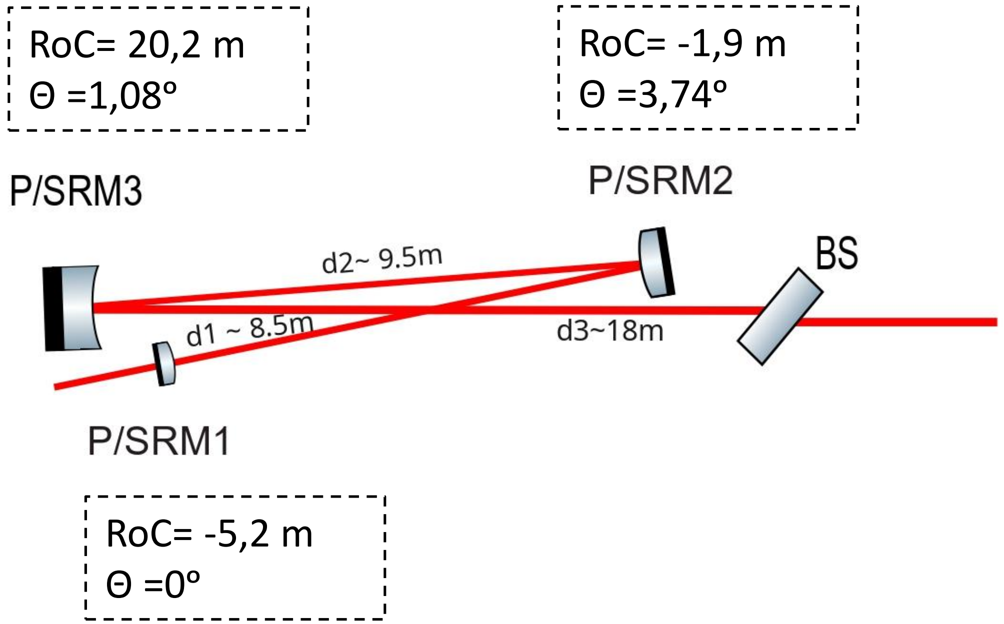
- **Solution: Use non degenerate recycling cavities.**

- To design stable non-degenerate recycling cavities:
  - Each high-order mode (HOM) has specific phase in the cavity called the **Gouy phase**.
  - Increasing the Gouy phase breaks the degeneracy of the cavity.
  - To increase the Gouy phase:
    - Increase the length of the cavity.
    - Focus the beam.



Design of the stable recycling cavities

- Geometrical constraints on the stable cavities design:
  - Limited infrastructure
    → Short focusing telescope of the cavity ($d_2 \lesssim 10$m)
    → Angle of incidence on P/SR3 $\gtrsim 1°$
- Design of the cavity:
  - Strongly curved mirrors → Spherical aberration losses.
  - Non-negligible angles of incidence → Astigmatism losses.



Goals of the study

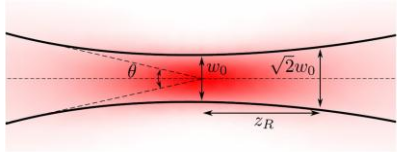
- We aim to calculate and characterize different types of losses in the recycling cavities:
  1. Losses due to astigmatism.
  2. Losses due to the mismatch between the recycling cavities and the Fabry-Perot cavities.
  3. Losses due to the RoC manufacturing error.
  4. Losses due to the mirrors surface imperfections.

- By studying these losses we aim to optimize the design of the recycling cavities.

FFT Simulation tools: OSCAR and SIS

- As tools we use OSCAR and SIS, two FFT codes developed within the LIGO-Virgo collaboration.

$\boldsymbol{E(x,y,z)}$



Propagate the laser in real space is computationally expensive.

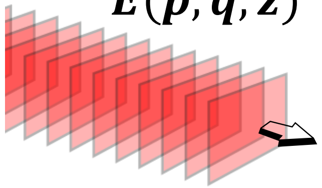
$\vec{\boldsymbol{E}}(\boldsymbol{x},\boldsymbol{y},\boldsymbol{z}+\Delta z)$

Decompose the laser beam to simple plane waves in Fourier domain

Fourier transform FT

Inverse Fourier transform FT^{-1}

$\widetilde{\boldsymbol{E}}(\boldsymbol{p},\boldsymbol{q},\boldsymbol{z})$



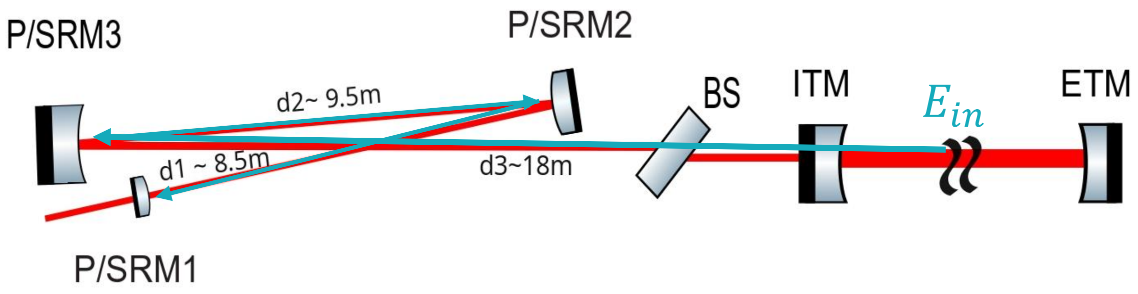
$\widetilde{\boldsymbol{E}}(\boldsymbol{p},\boldsymbol{q},\boldsymbol{z}+\Delta\boldsymbol{z})$

Propagate Δz by simple multiplication with phase $\widetilde{\boldsymbol{E}}(\boldsymbol{p},\boldsymbol{q},\boldsymbol{z})$**x** $\boldsymbol{e}^{\frac{\boldsymbol{i(p+q)}}{\boldsymbol{k}}\Delta\boldsymbol{z}}$

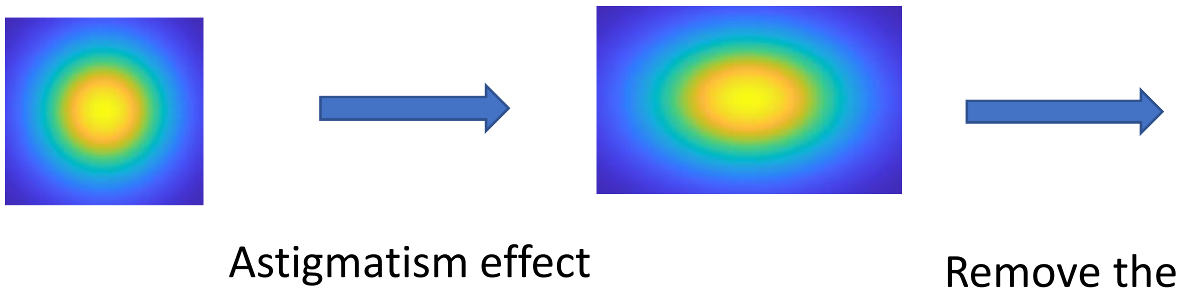
- If you have N points of the field; in real space number of calculations = NxN (**slow**). Using FFT method reduces number of calculations to NxlogN (**much faster**).
- After propagation of the beam, reflection, refraction and transmission though optical elements are simulated using matrix multiplication.

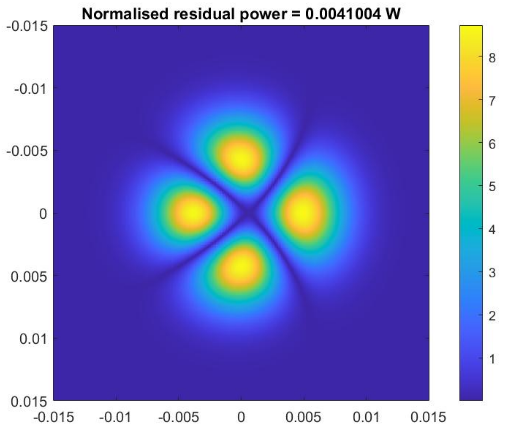
Astigmatism losses in the telescope of the stable cavities

- We simulate the beam propagation starting from the waist of the arm cavity through the telescope of the recycling cavity towards P/SR1.



- After the beam's reflection on P/SR3 it becomes astigmatic.

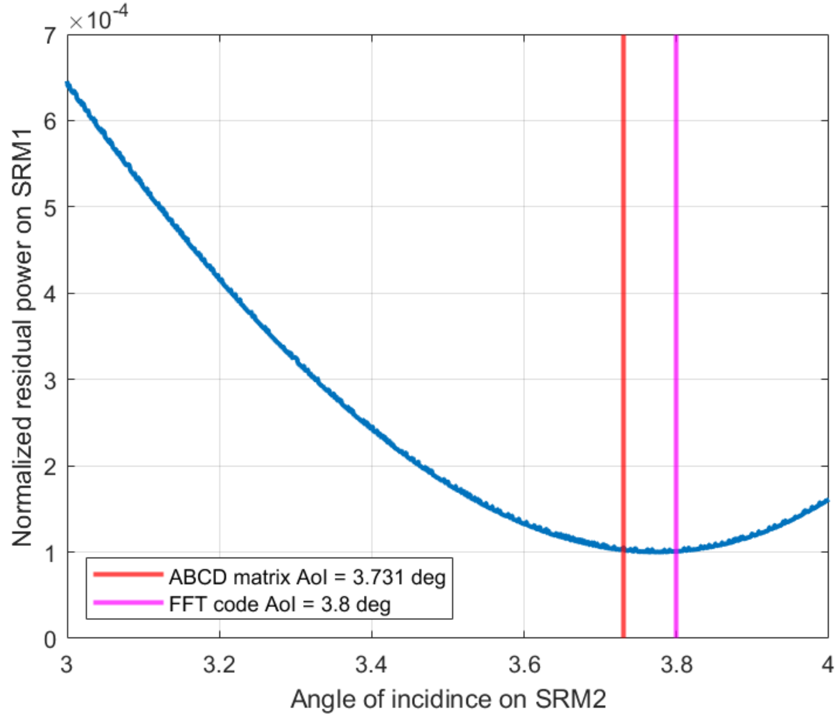




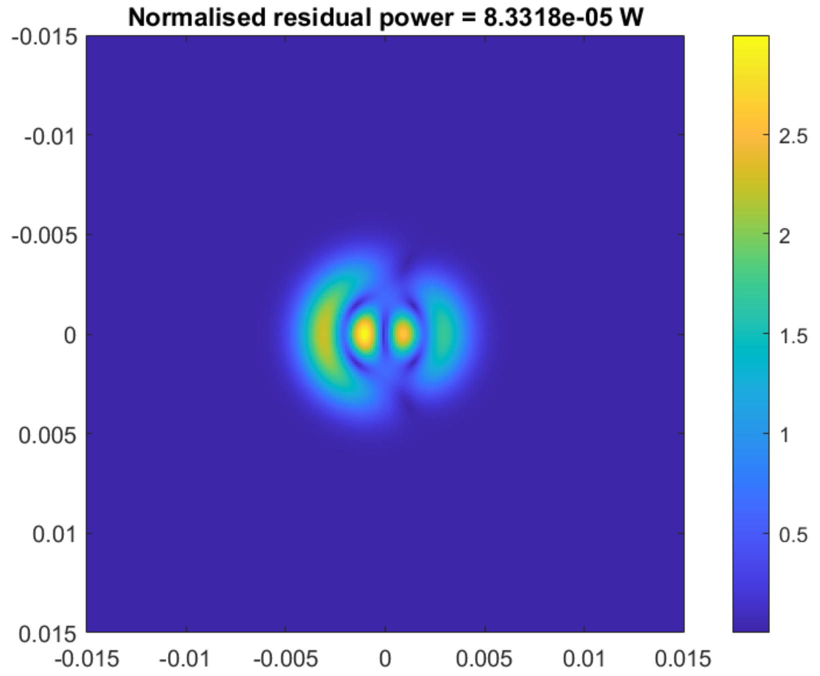
Power losses= 4000ppm

Astigmatism losses in the telescope of the stable cavities

- We optimize the angle of incidence on P/SR2.

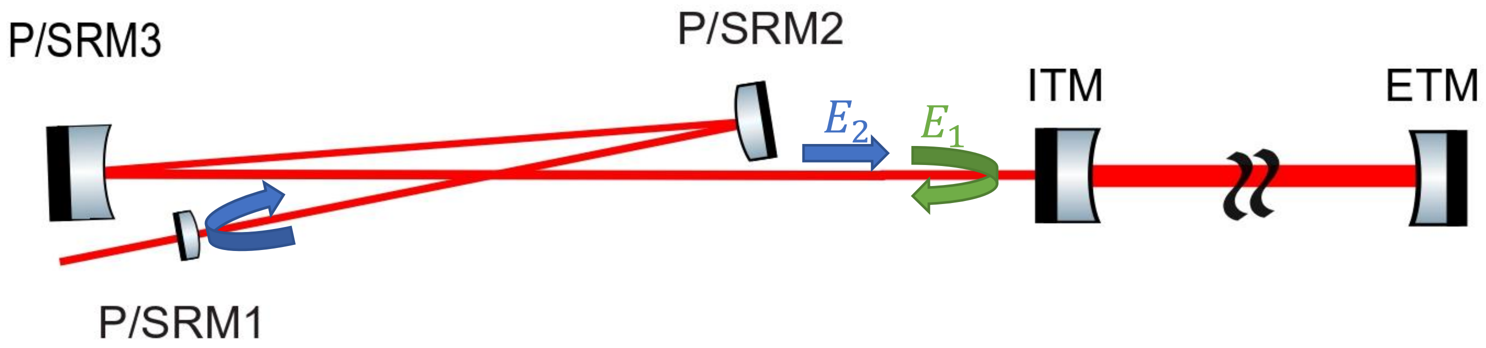


- Beam on P/SR1 after reflection on P/SR3 and P/SR2
  - Losses ~ 83ppm
  - Astigmatism compensation by a factor of 50



Round trip losses in the stable cavities

- We calculate round trip losses of the beam in the stable cavities.
  - It's the losses of the beam power after making a round trip in the cavity.



- We studied the overlap between Input field E1 and E2 on ITM.

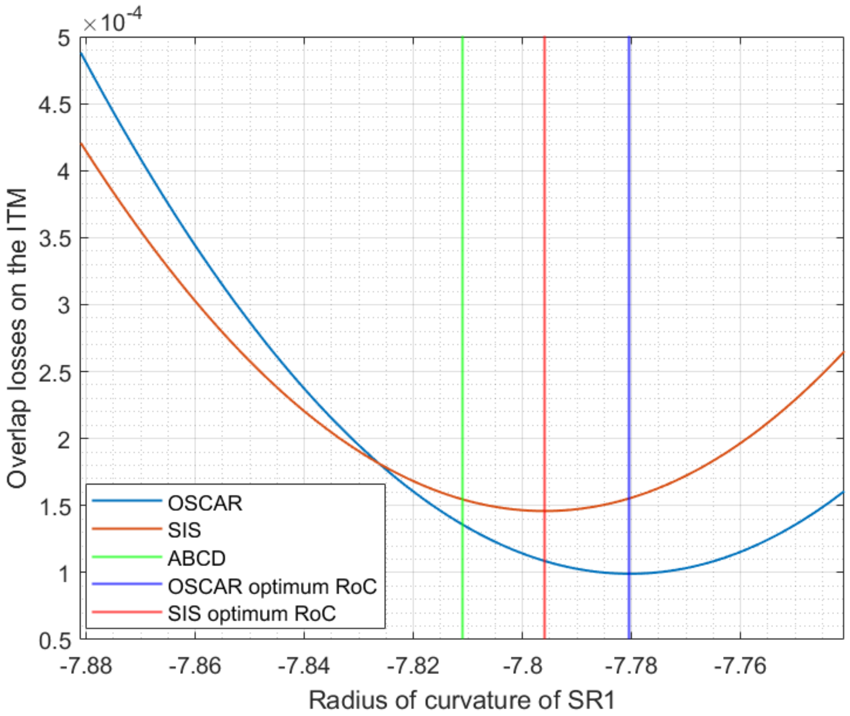
Overlap = $$\eta = \frac{\left(\int\int E_1(x,y,z)E_2^*(x,y,z)\,dx\,dy\right)^2}{\left(\int\int |E_1(x,y,z)|^2\,dx\,dy\right)\left(\int\int |E_2(x,y,z)|^2\,dx\,dy\right)}$$

Round trip losses (RTL)= 1 - **overlap**

- **We decrease the overlap losses / RTL by tuning the RoC of P/SR1.**

P/SR1 mirror radius of curvature optimization

- We minimize the round trip losses by optimizing the radius of curvature of P/SR1
  - We found a RoC uncertainty ~ 0.3% between the two simulation codes.

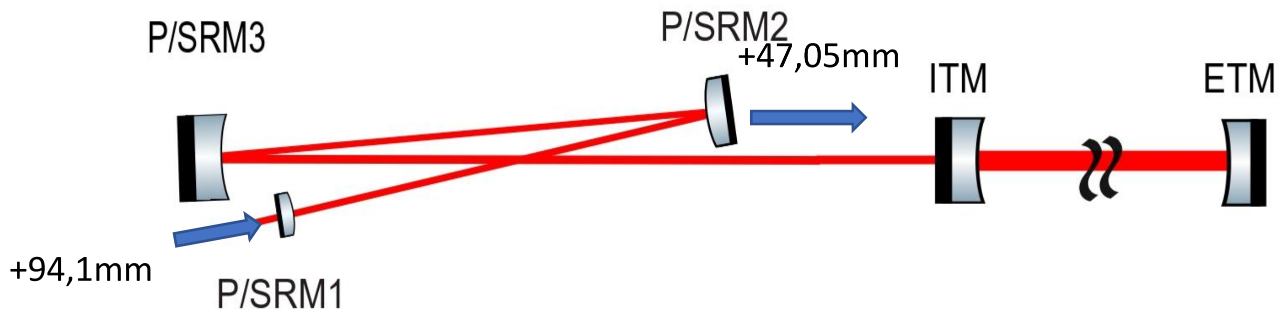


  - The results of the round trip losses using SIS:

Cavity	Conceptual design RoC	Optimum Roc P/SR1	Losses on ITM
PRC	-5.209m	-5.189 m	50 ppm
SRC	-7.811m	-7.778 m	150 ppm

Mirrors manufacturing: RoC error compensation

- Based on the design values of LIGO. We expect the polishers to provide mirrors with RoC error = ±0.5% for P/SR3 and ±1% for P/SR2 and P/SR1.
- This RoC errors make the cavity unstable.
- We can recover the cavity’s stability by changing the position of the mirrors while keeping the length of the cavity constant.
- For example: SRC with the worst case scenario RoC errors.



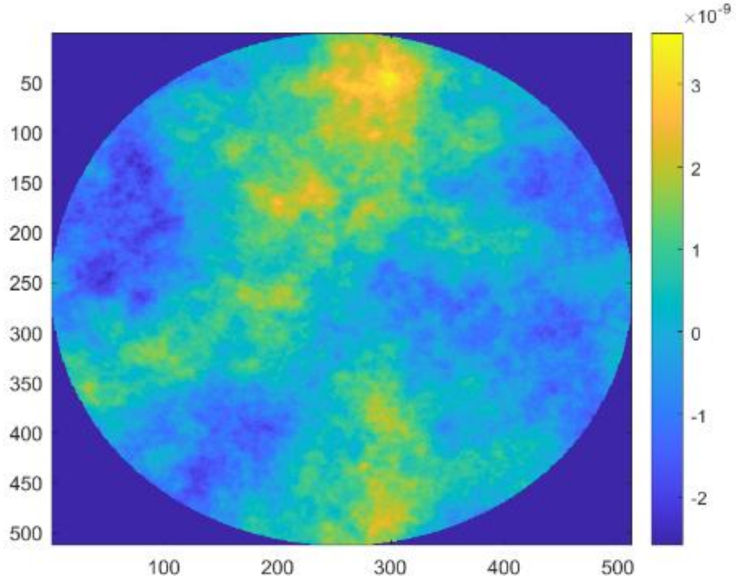
RTL without RoC errors	RTL with RoC error (+0.5%)	RTL with RoC error after compensation
99 ppm	Cavity unstable	99 ppm

Mirrors manufacturing: Surface imperfections

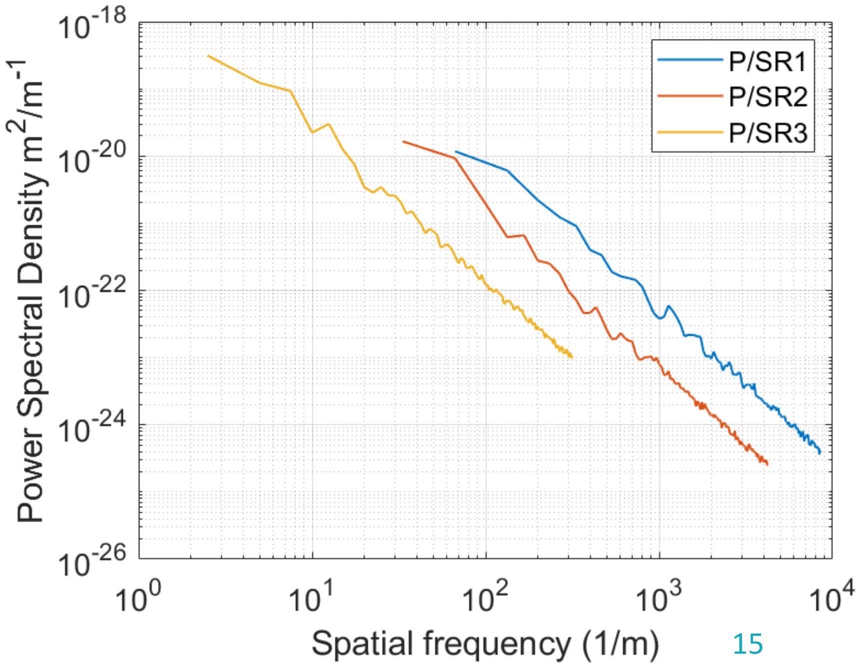
- Real manufactured mirrors have surface imperfections.
- Small imperfections can scatter light into unwanted directions or higher-order modes.

We simulate mirrors imperfections:

- We generate random fake mirrors' surfaces.
- The Power spectral density (PSD) tells us is how much roughness exist at different size scale in the frequency domain.
- We create surfaces with RMS (1nm, 2 nm and 5nm) defined over surface diameter D (~3x the beam size).
- The RMS is one value to quantifie surface roughness.



Real mirror surface



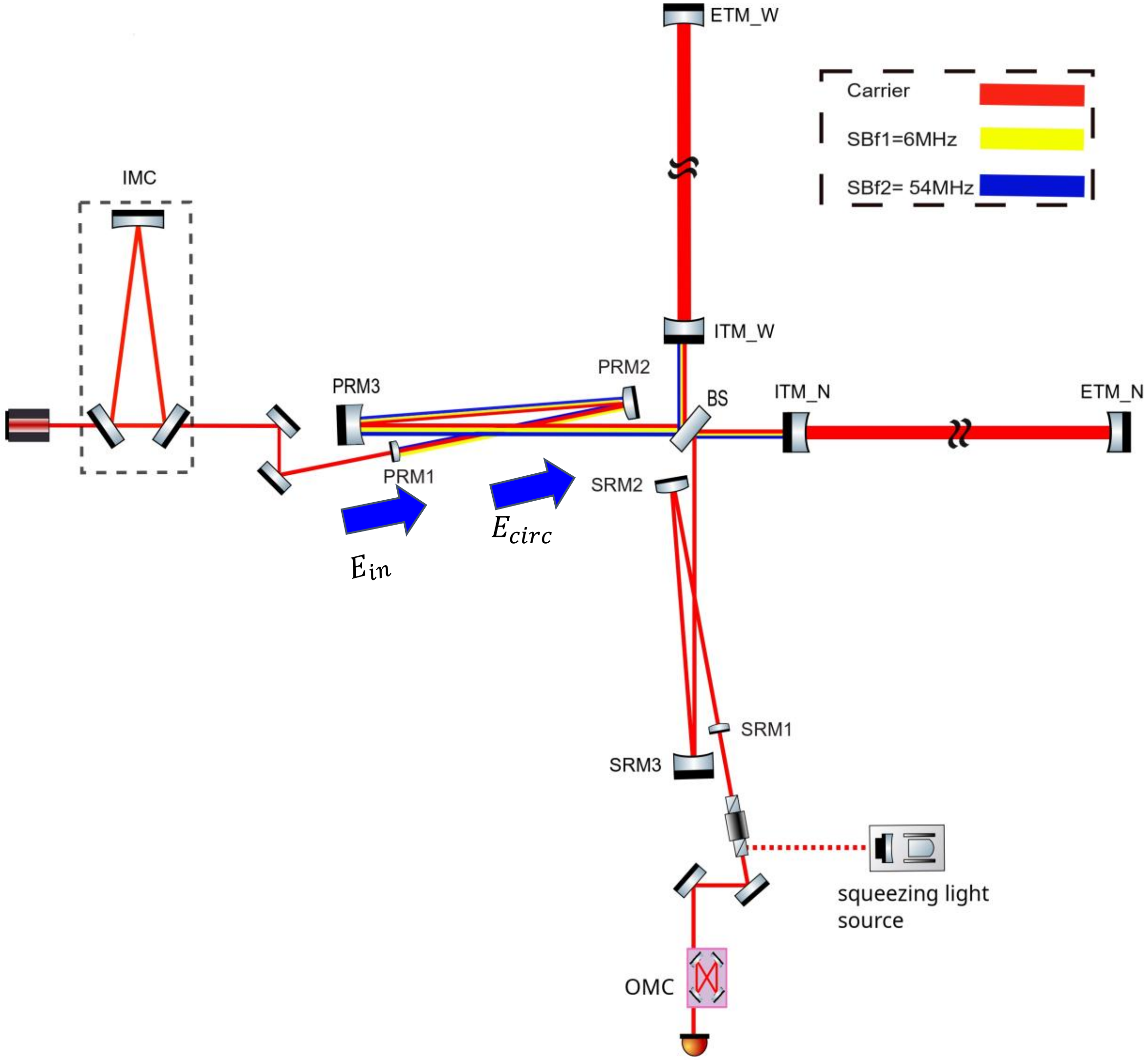
Locked Interferometer simulation: Gain of the PRC

- We simulate the full interferometer and we lock it as in real experiment.
- We inject:
  - Laser beam and modulation sidebands at frequency 6MHz and 54MHz.
- We calculate the gain the PRC:

$$G_{PRC} = \frac{P_{circ}}{P_{in}}$$

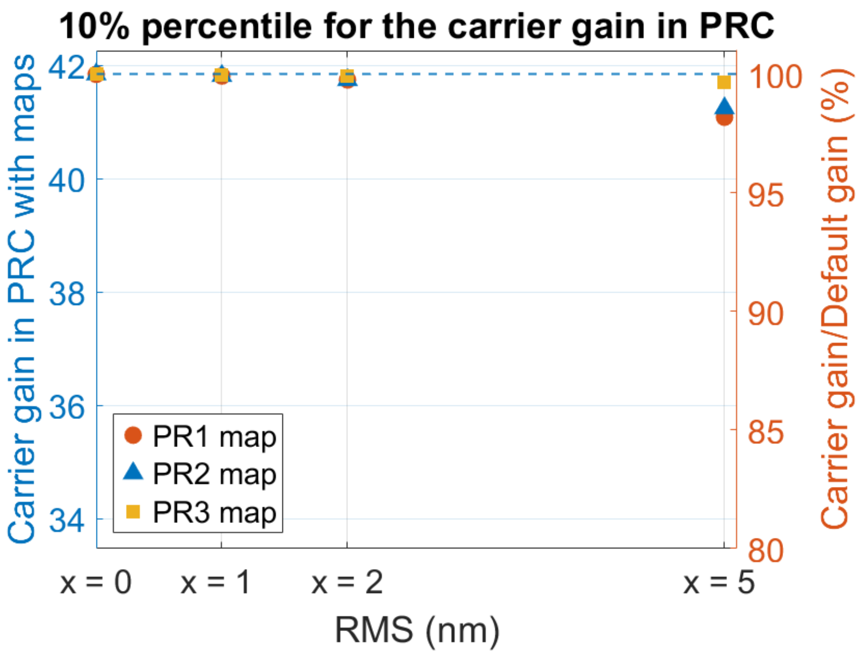
- We add surface imperfections on the mirrors surface and we calculate the gain percentage:

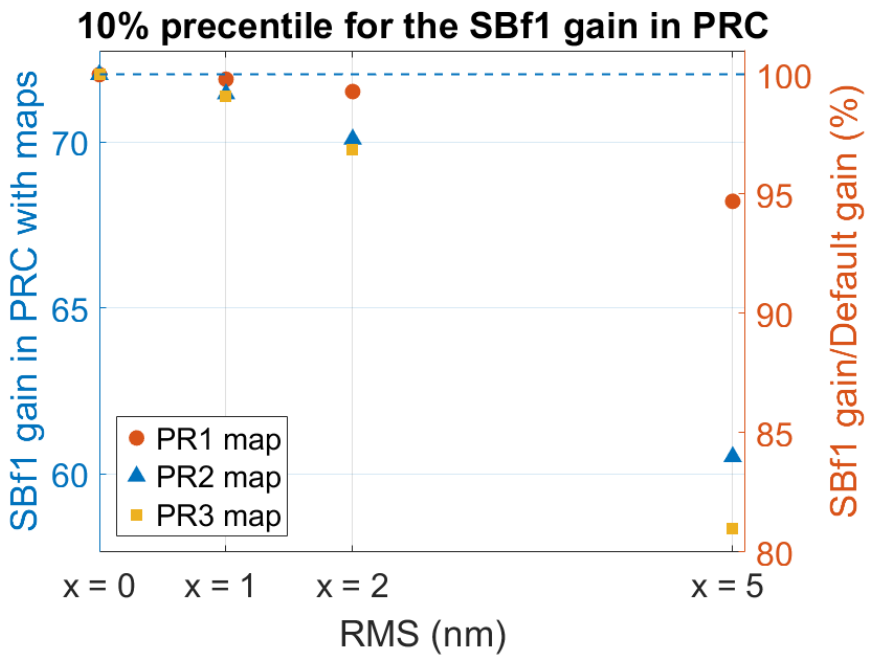
$$\frac{G_{maps}}{G_{NoMap}} \times 100\%$$



Locked ITF simulation: Gain of the PRC

- We add surface imperfections on each mirror individually to study each mirror contribution to the losses.
- We repeat the simulation with 100 different random fake surface on each mirror.
- We calculate the 10th percentile i.e. the value at which 90% of the simulations gives higher gain value.



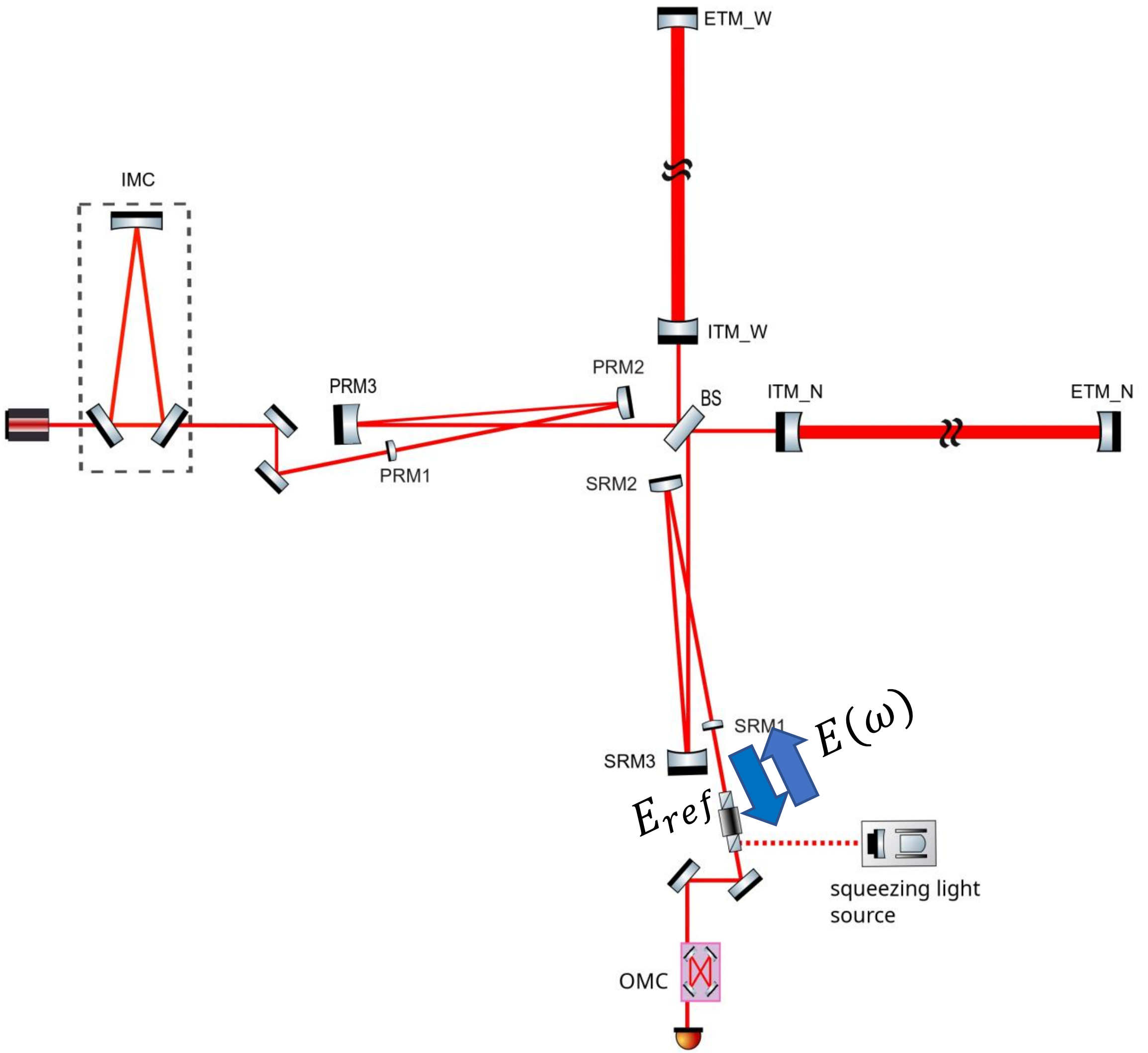


- **In conclusion: based on the modulation sidebands gain results, we accept mirrors' surface RMS ≤ 2nm.**

Locked Interferometer simulation: squeezing losses

- We simulate the locked interferometer.
- We inject a beam from the output
  - $E(\omega)$, shifted in frequency by $\omega \in [1Hz, 10kHz]$
- We calculate the reflected field.
- The losses are calculated by projecting the reflected beam on the TEM00 mode:

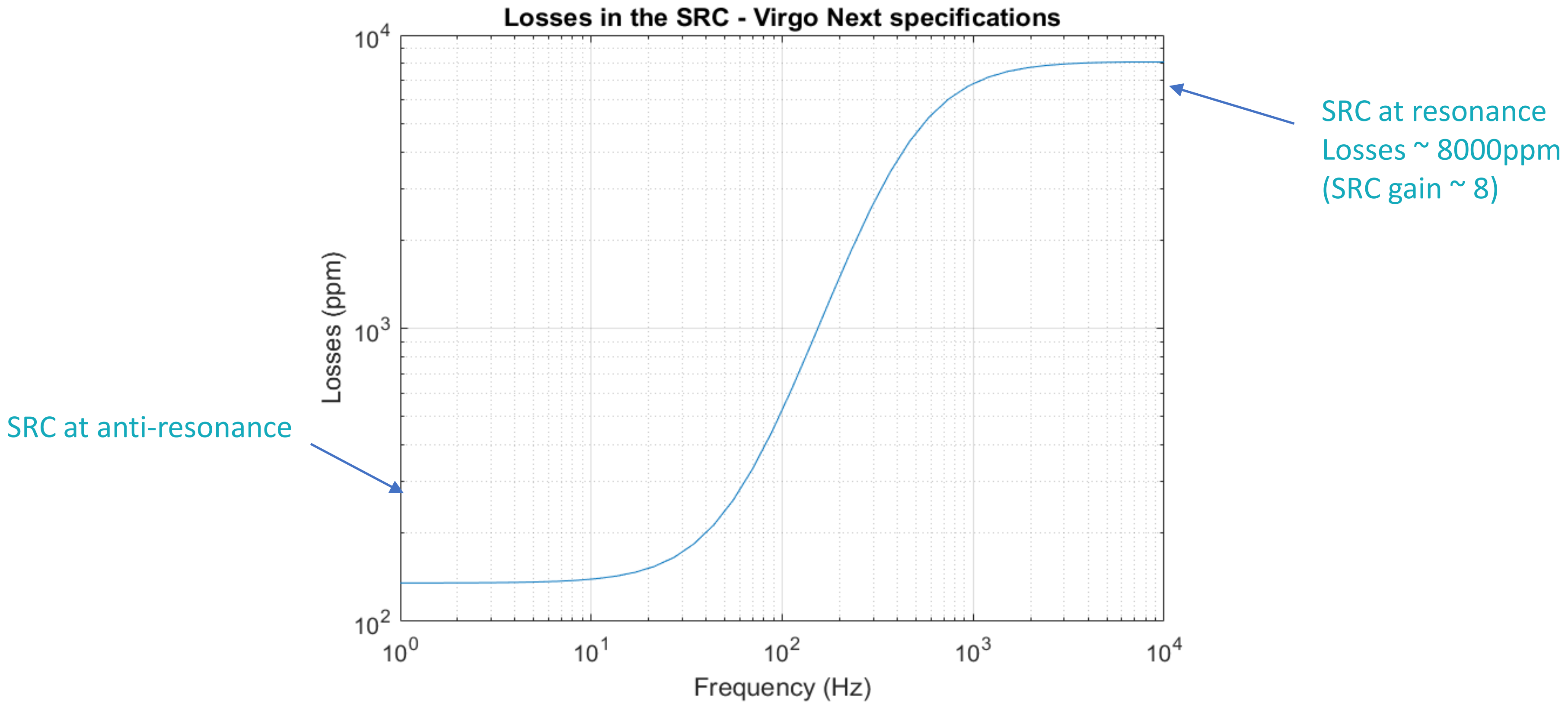
$$P = \left\| \langle E_{TEM00} | E_{Ref} \rangle \right\|^2$$
$$Loss = 1 - P$$



- Virgo nEXT squeezing specification:
  - Virgo nEXT is the further future upgrade of Virgo.
  - Squeezing is very senstive to the SRC losses.
  - **According to the squeezing specification: SRC Round Trip Losses (RTL) < 1000 ppm.**

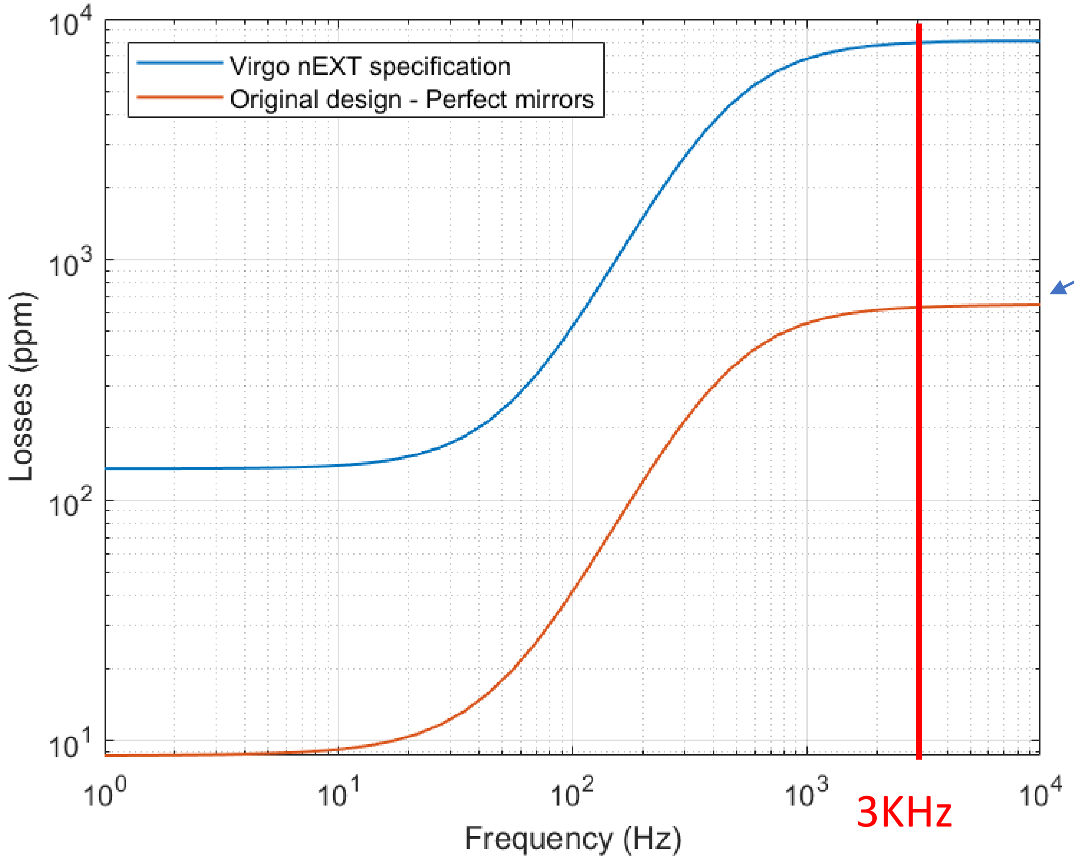
Locked Interferometer simulation: SRC Squeezing losses

- We set the angle of incidence to zero and we set scaler losses in the SRC =1000 ppm.
- We scan the SRC at different frequency in the range of the interferometer bandwidth.
- This gives us the reference curve of the losses that we shouldn't exceed.



Locked Interferometer simulation: SRC Squeezing losses

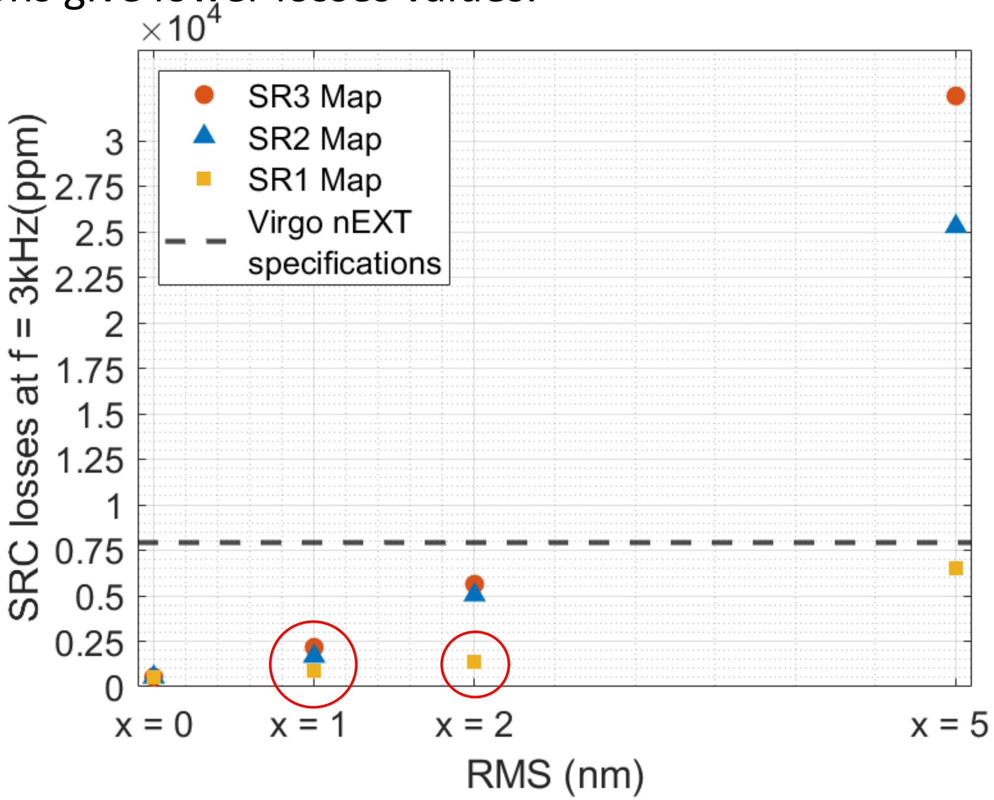
- We compare the losses of the SRC with the design AoI and with zero AoI.
- We calculate the losses due to the surface deformations at f=3KHz.



Design AoI
(effect of astigmatism)

Locked Interferometer simulation: SRC Squeezing losses

- We calculate the SRC losses at f = 3 KHz.
- We add imperfections on surfaces with RMS = 1nm, 2nm and 5nm defined over central diameter.
- We repeat the simulation with 100 different mirrors' surfaces, We calculate the 90th percentile i.e. the value at which 90% of the simulations give lower losses values.

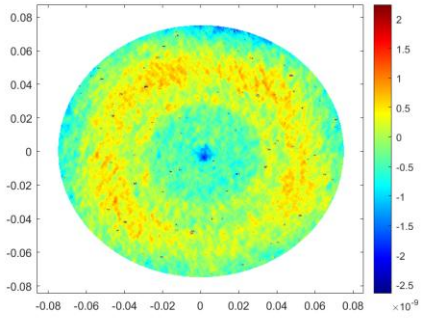


- For maps RMS = 5nm the losses exceeds the Virgo nEXT specification for the losses in SRC.

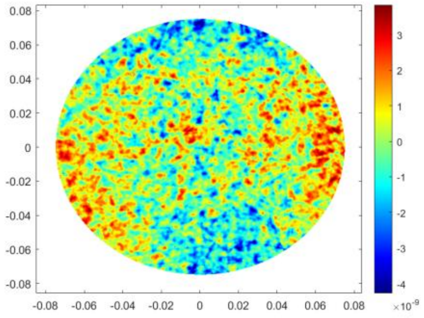
Locked Interferometer simulation: SRC Squeezing losses

- We have seen that SR3 is the most critical mirror for the losses in the SRC

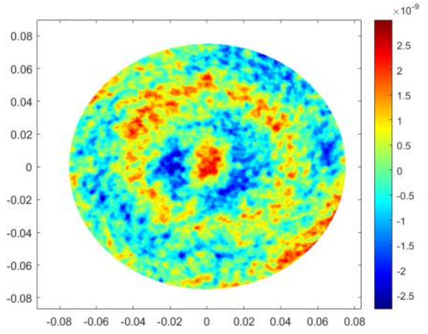
- **PR01**



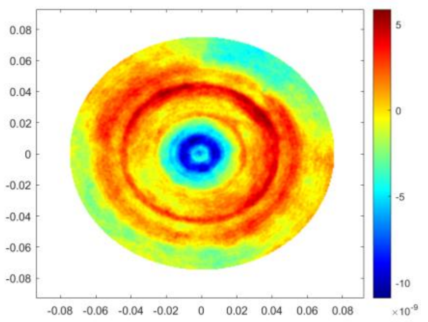
- **PR03**



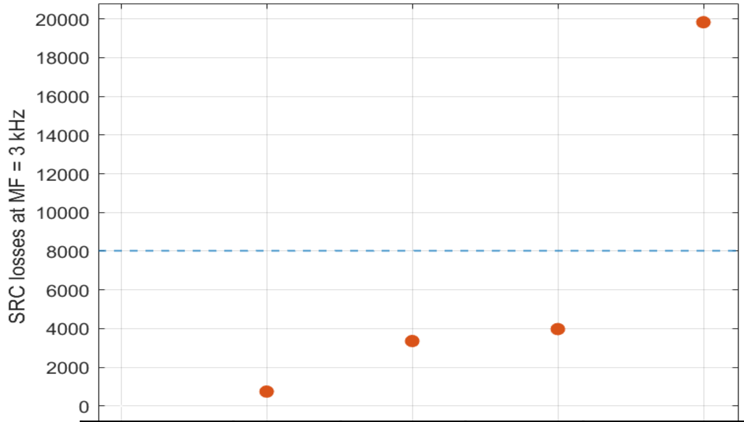
- **SR01**



- **SR-TS**

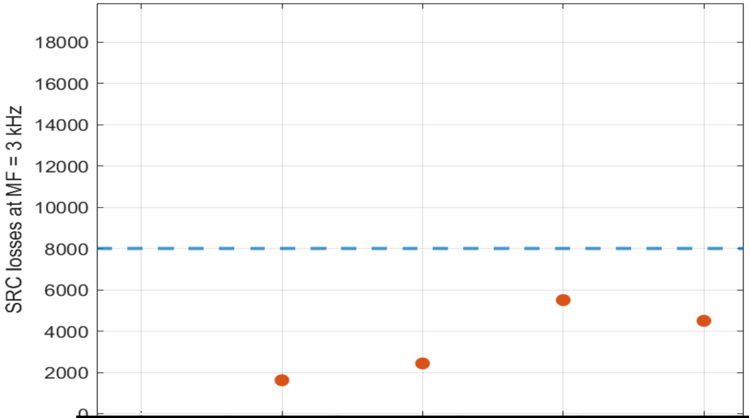


- We repeat the study of the mirror imperfections losses using real mirrors surfaces of Advanced Virgo mirrors.



Mirror map	PR01	PR03	SR01	SR_Thales
RMS(nm)	0,395	1,21	0,83	2,48

Scale the maps to RMS= 1nm



Mirror map	PR01	PR03	SR01	SR_Thales
RMS(nm)	1			

Preliminary specifications of the mirrors' surface RMS

- Based on the studies results we set the RMS specifications of the mirrors design.

	RMS (nm)	Central Diameter D (mm)
PR3	1	150
PR2	1	15
PR1	2	5
SR3	1	150
SR2	1	15
SR1	2	5

- **These results contributed to the technical design report of Advanced Virgo+.**

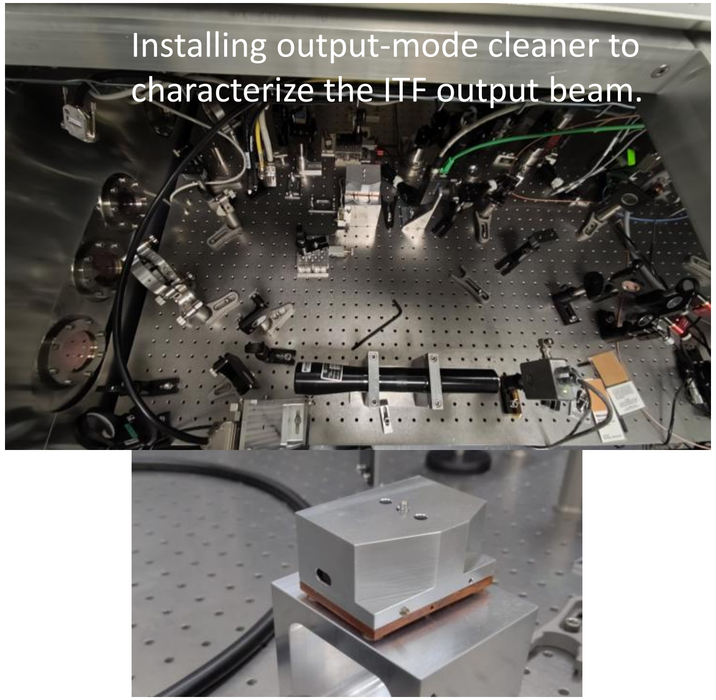
First year work summary

- **Scientific production during the first year:**
  - **4 technical Virgo notes.**
    - Beam aberrations and losses in the telescope of the stable recycling cavities for AdV+, 2024, W. Amar and R. Flaminio. link
    - Study of the mirrors design of the stable recycling cavities for adv+.virgo collaboration note, 2024, W. Amar and R. Flaminio. link
    - Study of the stable recycling cavities losses in advanced virgo+. Virgo collaboration note, 2025, W. Amar and R. Flaminio. link
    - Study of the stable recycling cavities losses in Advanced Virgo+ using Advanced Virgo recycling mirrors maps, 2025, W. Amar and R. Flaminio. link
  - **Contributing to the technical design report, the Optical design and simulation chapter.**
    - Virgo Collaboration. Advanced virgo plus for O5 - technical design report. May, 2025. https://tds.virgo-gw.eu/ql/?c=21680

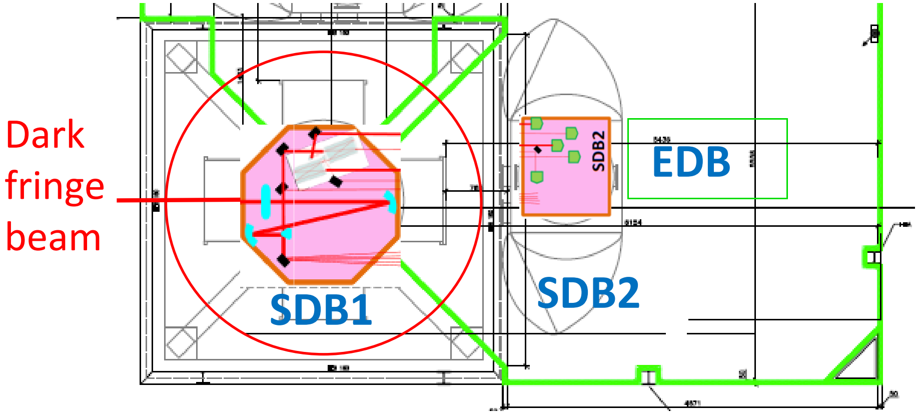
- **List of presentation:**
  - Virgo week Novembre 2024: Study of the P/SRC optical design for Adv. Virgo+, 2024, W. Amar and R. Flaminio, https://tds.virgo-gw.eu/ql/?c=21014
  - LVK week March 2025: The optical design of Advanced Virgo+ Stable Recycling cavities, 2025, W.Amar and R. Flaminio, LIGO-G2500738-v1, https://dcc.ligo.org/LIGO-G2500738
  - Virgo week June 2024 : Updates on the stable recycling cavities mirrors specifications, 2025, W.Amar and R. Flaminio, VIR-0669A-25, https://tds.virgo-gw.eu/ql/?c=21850
  - GdR ‘detectors developments’, June 2025, ‘Optical simulations methods for low-losses stable recycling cavities of Advanced Virgo+’
  - In addition: 4 presentations made for internal Virgo optical design and upgrade meetings.

Future work: Virgo detection benches

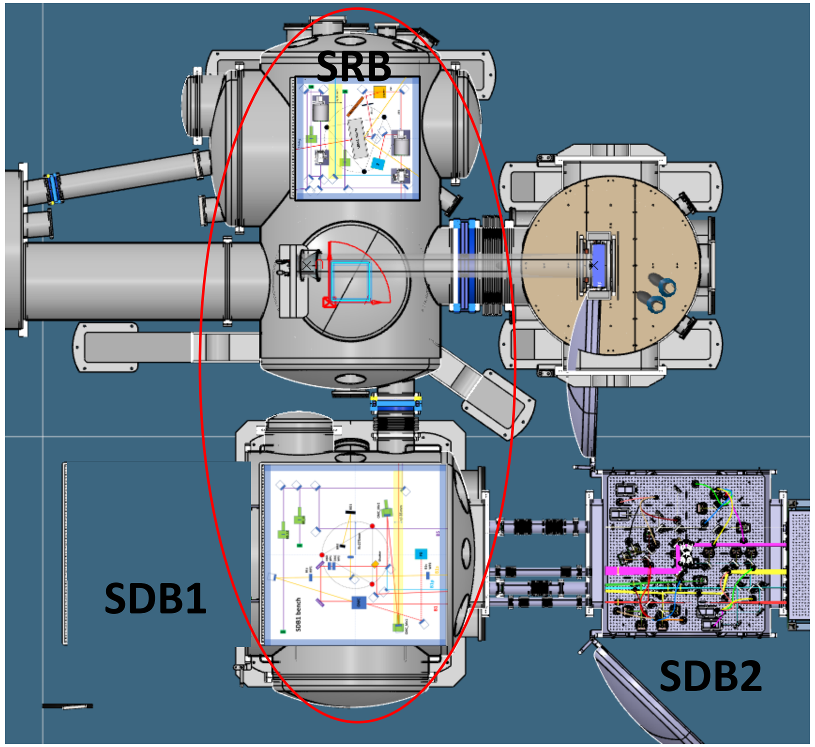
- The detection benches of Advanced Virgo are responsible to: extract, focus, filter and detect the beam.
- The detection benches are developed and constructed at the LAPP.
- During the last detector break I joined the commissioning work to install new optics on one the detection benches.



Current detection system



Future detection system



- Current design of the detection benches is not compatible with the stable cavities.
- **This requires future work of designing and building detection bench SDB1 and the reshuffling of other detection benches.**

Thank you!