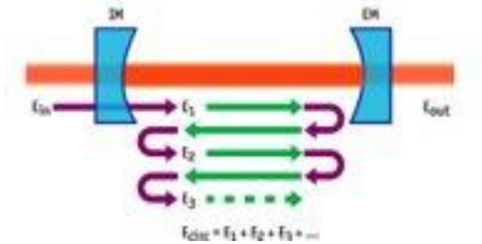
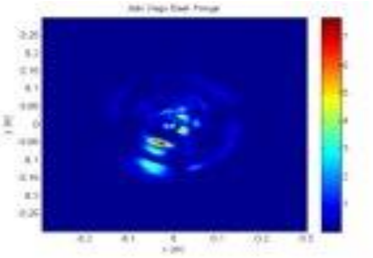




Software ecosystem for simulation and design of I/O GW Interferometer cavities

Sasa Topic, Michael Vervaeke, Simone Sorgato, Hugo Thienpont

VUB, B-PHOT, Photonics Innovation Center

Daniela Pascucci

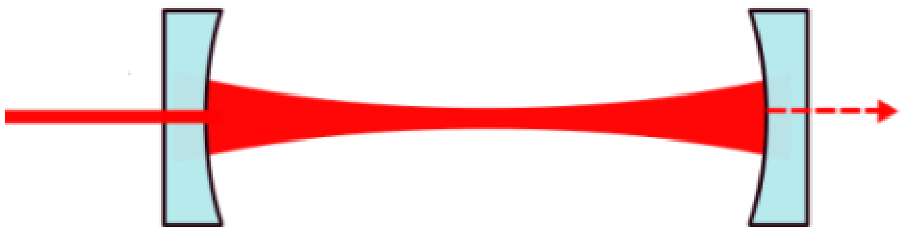
University of Ghent

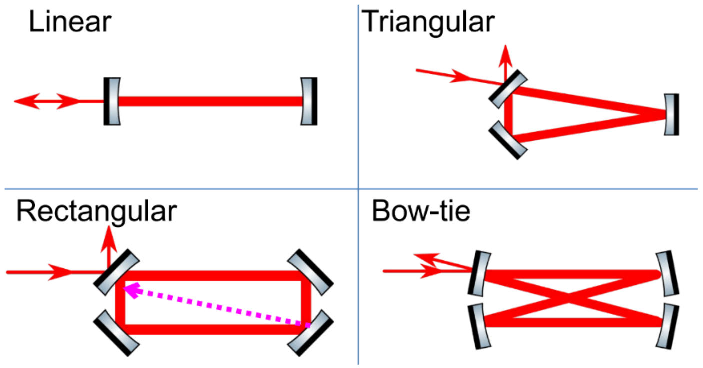
Tobias Schoon

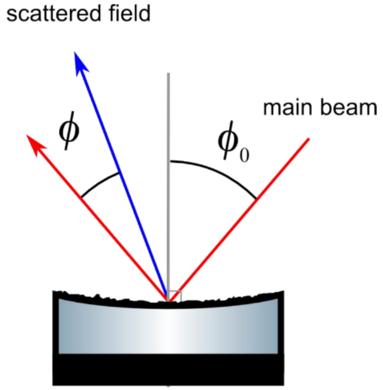
University of Maastricht

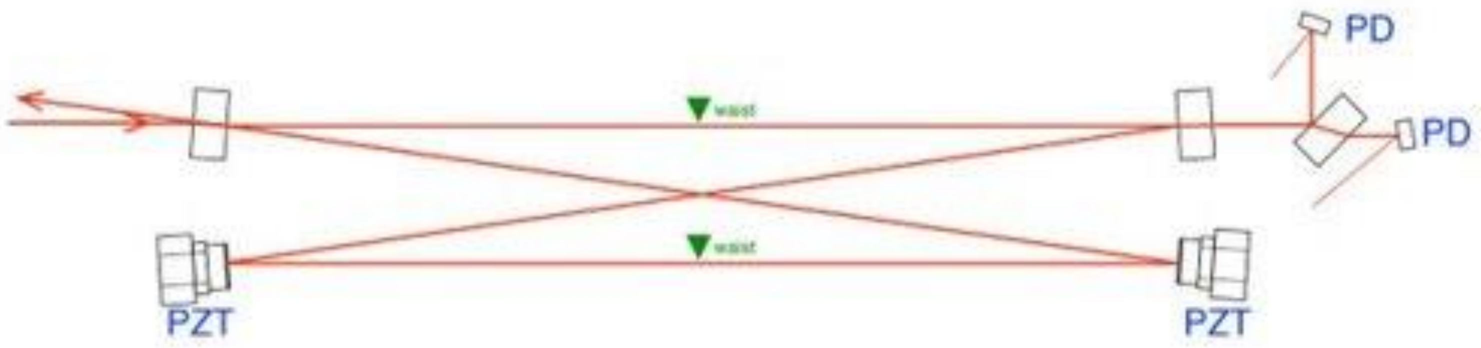
XI Belgian Dutch Grawitational Wave meeting: 23-24 October 2023, Maastricht, NL

How to make optimal I/O/filter cavity?





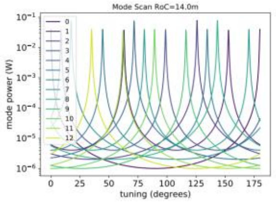


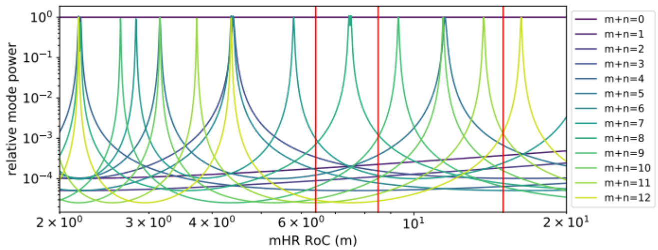


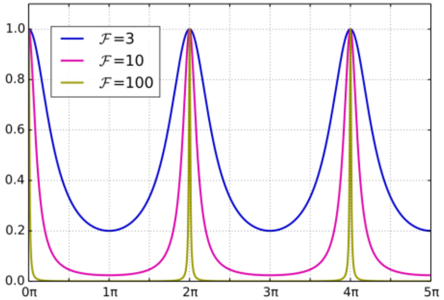
How exactly to design a resonant filtering cavity?

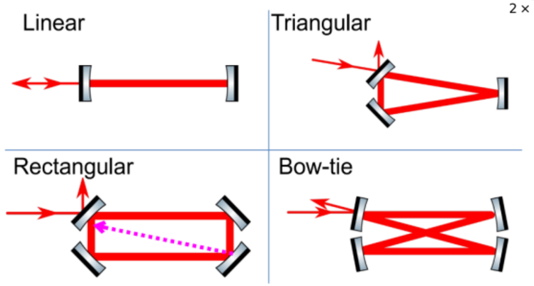
We have more than a few free parameters that need to be carefully chosen

- Length of the resonator
- Radii of curvature of curved mirrors
- Topology of the cavity
- Internal angles of incidence
- Finesse of cavity
- Apsorption loss





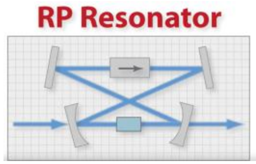


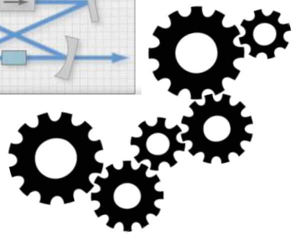


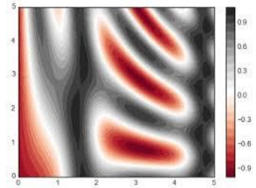
All the above heavily depends on the details of realization of a particular interferometer

Solution:

- **Use existing commercial and research tools** for design and simulation of resonant cavities
- **Make a numerical code** that gives us as an output some hints on parameter choice
- Make some sort of **exclusion plots**, **merit functions** and **vary parameters** independently to understand cavity behavior







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What we mean when we say *software ecosystem?*

- Ecosystem is *structured network of relations* among components that comprise some entity and it's behavior and is adaptive in relation to it’s specific surroundings.

- i.e. The whole is more than sum of it's parts.

- Structure and relation between parts bend depending on the external pressure and demands from the environment.

- **A structured poly-linked network of relations between nodes (specific codes and software products) that have specific and complementary/competing functions.**

Note on the choice of design tools of 3G detectors

Andreas Freise (23. Oct):

"New instruments need new (radically different and optimized) design procedures and new (fresh, inovative) thinking"

My free interpretation: New instruments need NEW streamlined and (preferably) NEW and/or proven design tools and CLEAR design cycle.

Why?

So that we can have fast prototyping, qualitative improvement in design capabilities and at least order of magnitude better I/O cavities that that of 2G+ instruments.

=> wisdom and know-how from LIGO/VIRGO design can be used as a consulting and guiding voice but not as primary tutorial or universal know-how source!

What you will not see in the list:

A lot of old software.
Discontinued software.
Software whose sole developers retired or worse :(.
Software that is used by small sectarian-like groups or is abandoned.
Software with opaque functions and very steep learning curves.
Software that is so intricate that it appeals to mysticism.
Software based on C/C#/Fortran95 (not really).
general noise calculating packages for entire Interferometers (i.e. PyGwinc)
You will not see Optickle, e2e, FOG, SIS15, MIST etc…….
You will not see an approach that favorizes fetishism of completely R&D obscure codes, we should embrace user friendly and even commercial codes

What you will see:

Software that is in constant development and have dedicated curators/teams.
Commercial software.
Open-source software (Python/Matlab) with intuitive user interface and outputs.
Software from young and middle-aged developers.
New software – not legacy
Synergistic holistic software workflow

For general list of (almost) all of the software see this list compiled by Sebastian

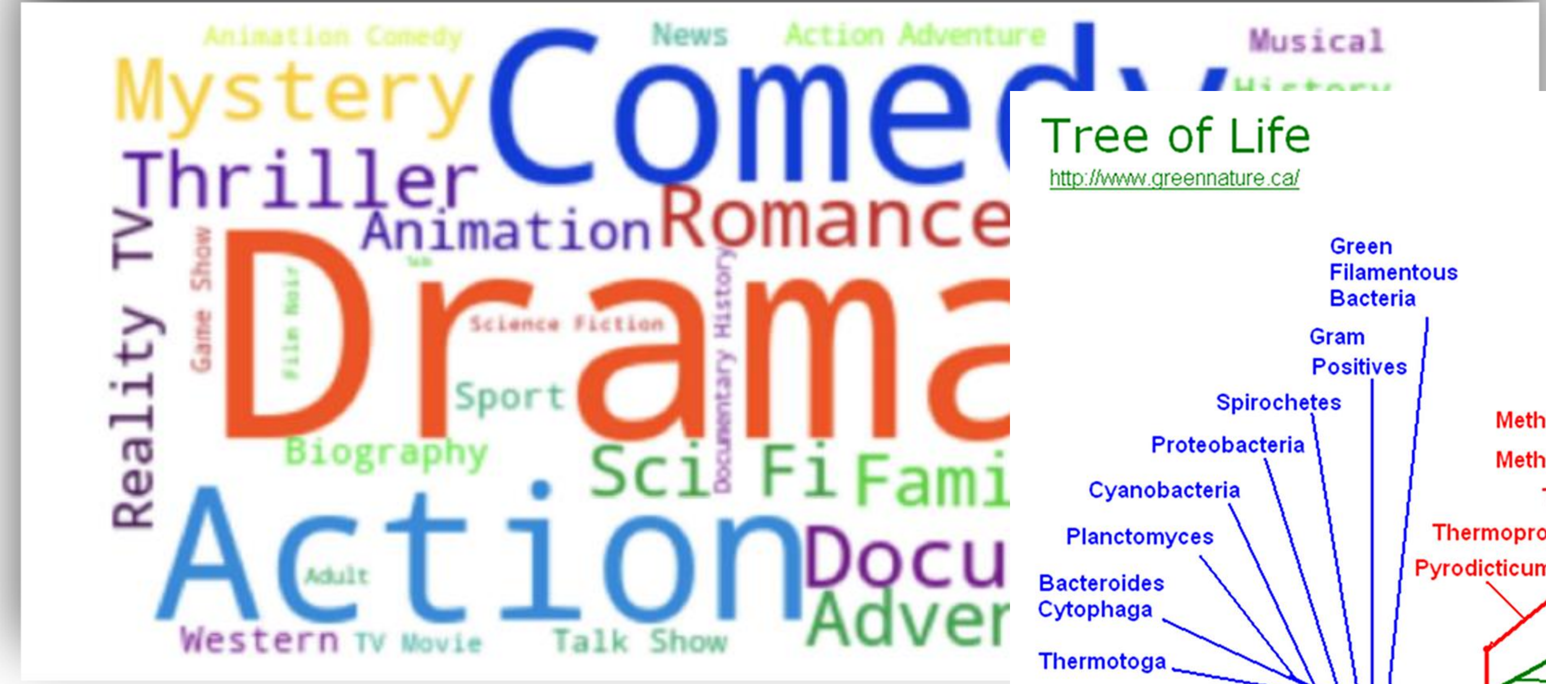
What piece of software does what?

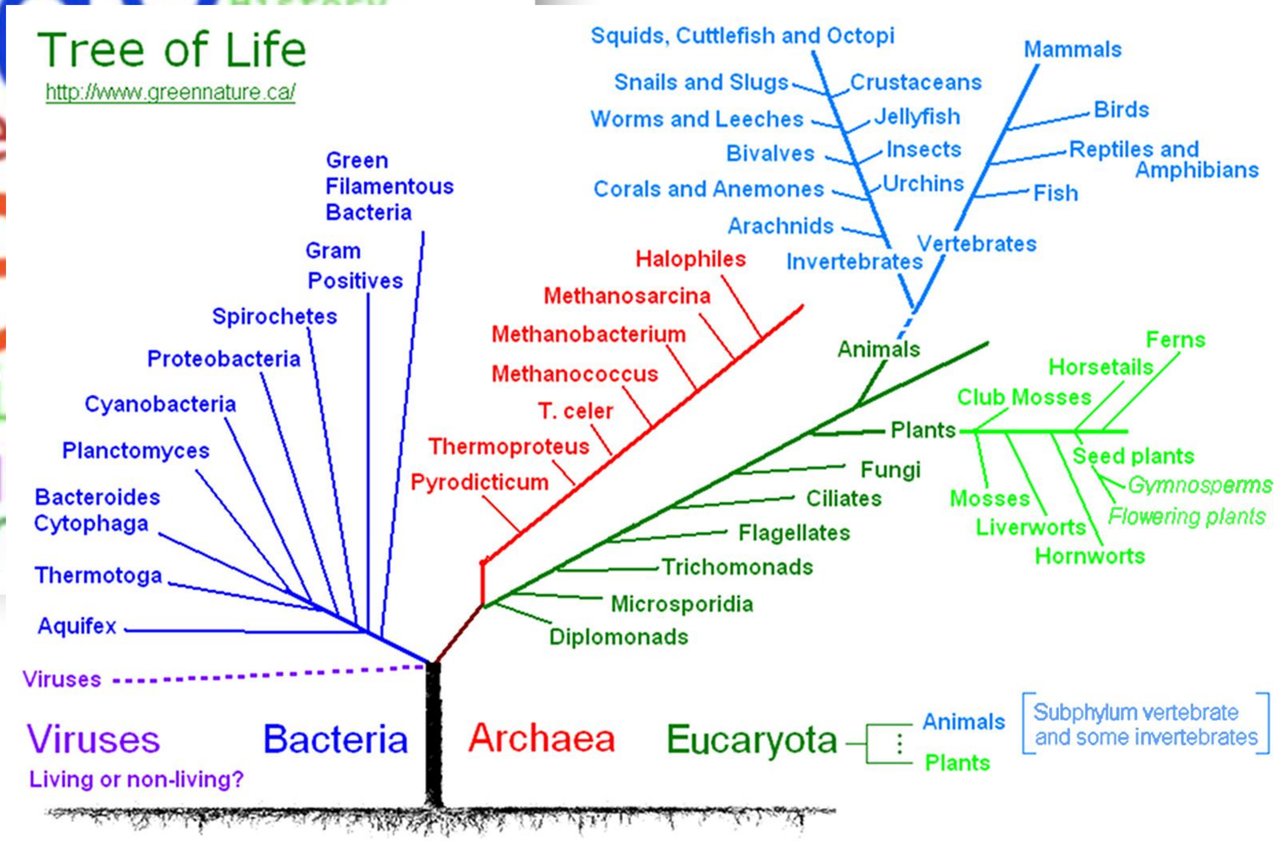
Software/Features	FINESSE 2/3	OSCAR (Matlab)	VirtualLab	Resonator Rp Photonics	DarkF	Optocad	JamMT
Usage/main feature	For simulations/preliminary paraxial approx design	For FFT simulations with HOM's and mirror maps	For physical design and optimisation	Custom made for laser resonator design	static and dinamic perturbations + surface defects	For layouting	Tool for mode matching
FFT							
Modal							
Frequency							
HOM							
Guoy Phase							
Modulation SB							
Mirror maps							
Graphical I/O							
GUI							
Cavity scan/field visualisation							
Optimisation							

Scan the QR code to edit it or access it via the link: https://tinyurl.com/ejwnb7pd

An (potentially big) list……. what parameters to value and how? How to combine the codes? In what order and for what reason?

Let's divide software by genres?! v !?





Paraxial software/ray-trace/Gaussian beams

- FINESSE 2/3 (https://www.gwoptics.org/finesse/ https://finesse.ifosim.org/docs/develop/index.htmlv)
- OptoCad/IfoCad (https://www.aei.mpg.de/ifocad)
- Zemax (https://www.zemax.com/)
- JamMT (http://www.sr.bham.ac.uk/dokuwiki/doku.php?id=geosim:jammt)
- Resonator RP (https://www.rp-photonics.com/rp_resonator.html)
- First Time Right (http://first-time-right.b-phot.org/webapps/home/session.html?app=FTR)

FFT codes

•OSCAR (https://nl.mathworks.com/matlabcentral/fileexchange/20607-oscar)

Developed by Jerome Degaleix of LMA. It is FFT code that calculates electric field distribution and cavity content.

•DarkF (https://sourceforge.net/projects/darkf/)

Developed by Michael Pichot from ARTEMIS. Useful for cavity design.

Physical/Maxwell solver software

- Virtual Lab (https://www.wyrowski-photonics.com/)

For now only at routine use at B-PHOT.

It is RCWA complete Maxwell solver that can do A LOT of things. Envisioned as swiss-army knife of optical design software.

But in generality there must be weak spots i.e. it is not specialized for GW Interferometer design.

It has powerful optimization algorithms
Different modes of operation (sequential/nonsequential), can calculate phases and amplitudes of field, layers/stacks, polarization etc.

Other – last but NOT the least (pieces of puzzle made by *young* researchers

•Semi-analytic code for modal coupling (https://tinyurl.com/3hfcvtzw)

By ST (VUB B-PHOT – present)

•jsCav (http://sestei.github.io/jscav/)

By Sebastian Steinlechner (UM, ET PF WP 6 leader – present)

•Zernike mirror map decomposition (https://git.ligo.org/IFOsim/ifosimworkshop2023/-/tree/main/VirtualMaps)

By Anna Green (Nikhef/LIGO/VIRGO - present)

What is following?

- Condensed review of 6 representative and most useful pieces of software

- Complementary usage

- Recommended ordering/workflow of software application in designing of OMC

Condensed Software for OMC design/simulation review

OSCAR (FFT code, scalar wave propagation)

Finesse (modal basis -klm coefficients - paraxial approximation: ABCD matrices)

RP Resonator (same as Finesse but lays on ABCDEF matrices foundation, handles misalignment, has script language like Finesse)

VirtualLab (Physical, RWCA approach, full vectorial FFT approach. Can handle phase elements, and is a proper OPTICAL DESIGN tool)

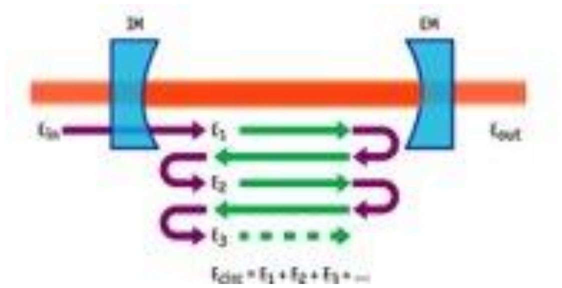
Semi-analytical code for cavity content simulation

First Time Right code for design and optimisation of imaging and nonimaging optics

jsCav code for calculation of FP cavities eigenmodes (includes HOM)

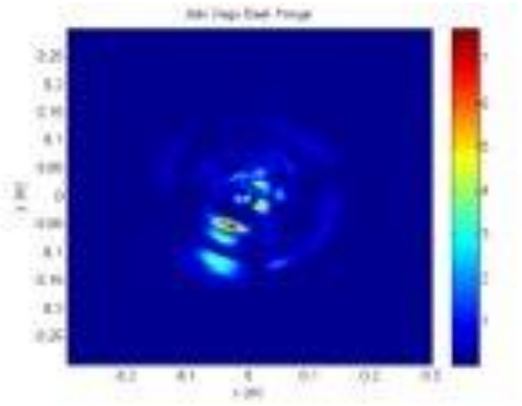
OSCAR (FFT code)

- We all know Jerome and know about/have worked or will work in OSCAR.



Finesse (Frequency domain simulation in HG/LG modal basis)

- Andreas is here! Finesse 3 it is (almost) a silver bullet for GW Interferometer design!



RP Resonator – commercial software

Easy to define resonator structures, additional calculations or optimizations

Can easily parametrize designs

ABCD(EF) matrices that account for tip/tilt

Freely define detailed optimization goals in the form of a **figure-of-merit function**

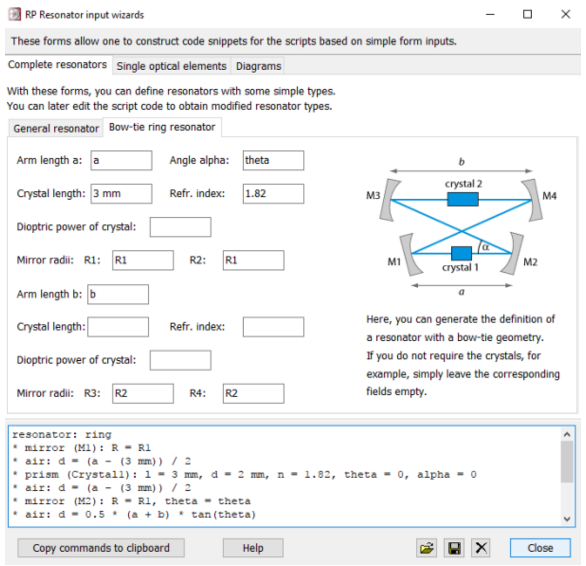
Custom made for resonator design

Useful in fast prototyping and for crosschecks

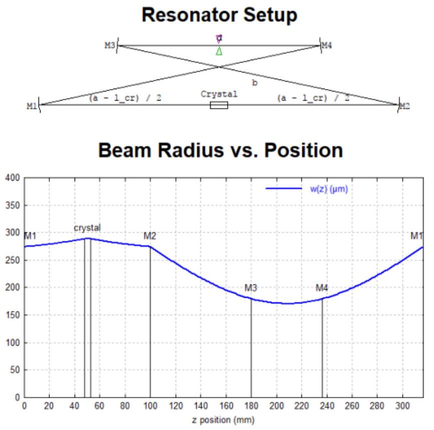
Output as scheme and as Zemax/VL/OptoCAD readable file

Easily adaptable for OPO construction, freq. Doubler calculations etc.

It is a linchpin in following design workflow!




```
; -----------------------
diagram 1, size_px = (600, 180):

draw resonator, "Resonator Setup", showfocus

; -----------------------
diagram 2:

"Beam Radius vs. Position"

x: 0, L_res / mm
"z position (mm)", @x
y: 0, 400
frame
hx
hy

f: w(x * mm, lambda_ref) / um,
  "w(z) (µm)",
  color = blue,
  width = 3
```



VirtualLab – commercial software

- By words of the creators they made a tool capable of solving ANY optical design problem. Many incorporated solvers.
- Let them speak

Semi-analytic code for simulation of cavity content (see poster)

- Calculation of important features of bowtie mode cleaner cavity
- Evasion regions (regions of high transmission of SB and HOM – necessary to know frequency and power of SB).
- Independent variation of Finesse, misalignement and mode mismatch in order to understand the role of those parameters to performance of OMC.
- Looking at carrier, sb and HOM content of cavity
- Graphical output to find appropriate ranges of values for L and RoC
- Construction of OMC with realistic parameters (L, RoC, alpha, Finesse) for sub-SQL performance

- Assumptions for this semi-analytic code:

Modeling of HOM power spectrum distribution as power law

Linearization of Hermite Gaus polynomial for calculation of modal crosstalk coefficients

Bundling up of all of the missalignement and mode mismatch into purpose designed real valued variable

Power distribution vector (intuited from LIGO and KAGRA reports)

First time right

- Proprietary B-PHOT (F. Duerr, H. Thienpont) code developed for eikonal equation derived wave-fronts based optimization of reflective/refractive surfaces.

- Mirror based design - folded bowtie can benefit from this

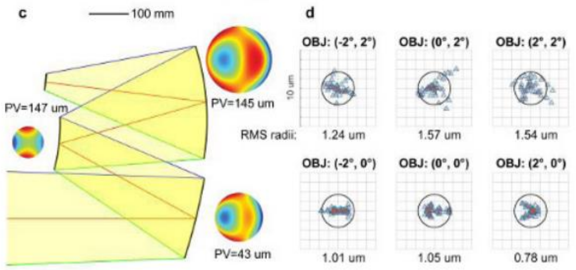
- Graphical interface and graphical hints (spot size, deviation from sphere etc.)

- Solving Eikonal equasion for finding optimal shape of mirrors to optimize to some selected metric

- Gives hints for surfaces in terms of Zernike decomposition

- Cancel-out beam distortion with complementary phase mask/aspheric interface

- Can add value to classical designs with minimal effort



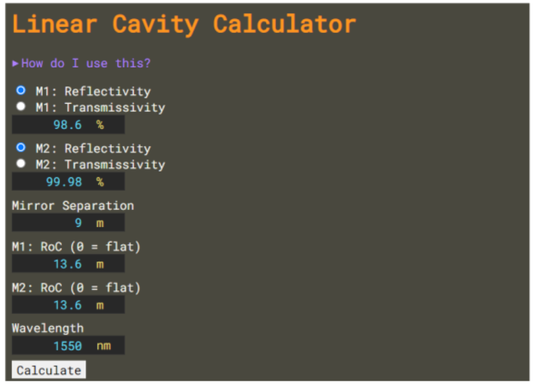
https://doi.org/10.1051/epjconf/202125502001

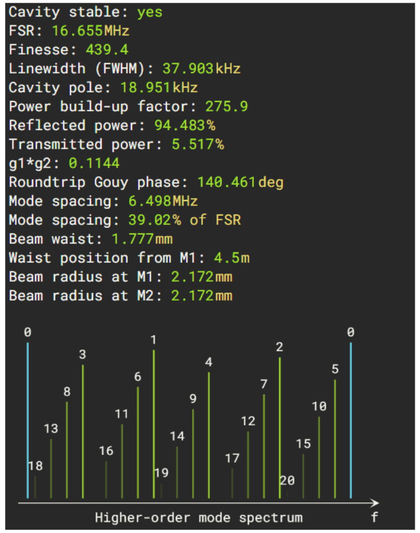
jsCav

- Calculates cavity parameter via only few given key values
- Gives out a qualitative modal composition of cavity

- Probably based on some Python ABCD matrix code (Sebastian?)
- Does not include sidebands

- Very useful in fast prototyping





Hot to combine codes? Maybe pair-up complementary software

- **Paraxial** and **FFT** software are natural complements

FINESSE, RpResonator, OptoCad vs OSCAR,VirtualLab, DarkF

- **Dynamic** and **static** softwares are natural complements too

FINESSE, DarkF vs OSCAR (somewhat), VirtualLab…

- Different m**odal basis** (x-y plane FFT vs beam eigen-modes LG/HG)

OSCAR, DarkF, OptoCad vs FINESSE, RP Resonator

- Softwares with/without input of mirror maps (former are in great advantage)

And so what?

- What to do with this menagerie of software solutions?
- Find a way to combine them into comprehensive and definite workflow!
- Confederation of softwares!

Back of the envelope design of OMC

Initial parameters *ab initio* + informed guess

- Determination of Finesse:

Roundtrip loss and realistic coating precision =>

R of approx. 98.5 => **Finesse of 250**

- Rejection of background noise:

We should go to 1/100000 - just go with high finesse (not a possibility) and/or substantial evasion of HOM, SB's and cavity induced eigenmodes - that implyes **Length (RTL) of about 2m** which means **FSR of about 250 MHz.**

- Determination of topology:

Backscattering and squeezing determine topology of 3G OMC. 2 G detectors have proven that FP linear cavity are not good choice because of scattering into the interferometer.

Squeezing favors as much of internal angles as possible because of decrease of backscatter (that decreases destruction of entanglement) so it implies bowtie! **Bowtie geometry It is** i.e. a traveling wave.

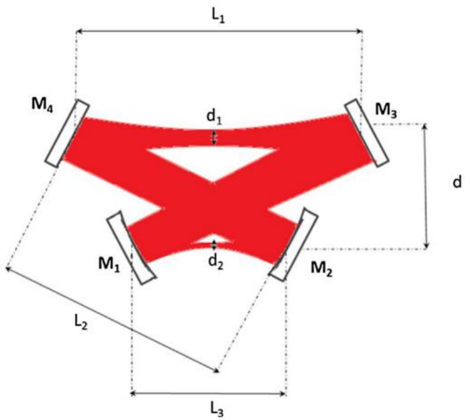
- Determination of angles:

Constraints of Guoy-phase induced frequency splitting (If higher than linewidth causes 2 resonances of fundamental TEM mode). **Internal angles of bowtie lower than 12 deg.** Bigger angles unfavorable because of astigmatism.

***NB: Our OMC design approach will try to cancel the angle induced astigmatism with freeform mirrors.

Initial selection of parameters

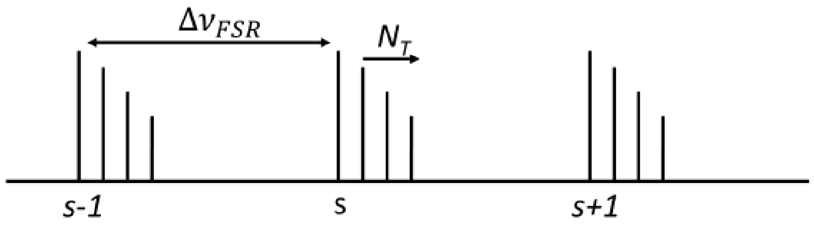
Property	Symmetric ring
g_1	$1 - \frac{d_1+2d_2}{R}$
g_2	$1 - \frac{d_3}{R}$
Path length	$L = d_1 + 2d_2 + d_3$
Waist(s)	$\omega_0^2 = \left(\frac{\lambda R}{2n\pi}\right)\frac{\sqrt{g_1 g_2(1-g_1 g_2)}}{g_1}$ ${\omega'_0}^2 = \left(\frac{\lambda R}{2n\pi}\right)\frac{\sqrt{g_1 g_2(1-g_1 g_2)}}{g_2}$
ν_{nmq}	$\left(q + (n+m+1)\frac{\cos^{-1} \pm\sqrt{g_1 g_2}}{\pi}\right)\frac{c}{L}$
FSR	$\frac{c}{L}$



$$\begin{pmatrix} A_1 & B_1 \\ C_1 & D_1 \end{pmatrix} = \begin{pmatrix} 1 & \frac{L_1}{2} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -\frac{2}{R} & 1 \end{pmatrix} \begin{pmatrix} 1 & L_3 + 2L_2 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -\frac{2}{R} & 1 \end{pmatrix} \begin{pmatrix} 1 & \frac{L_1}{2} \\ 0 & 1 \end{pmatrix}$$

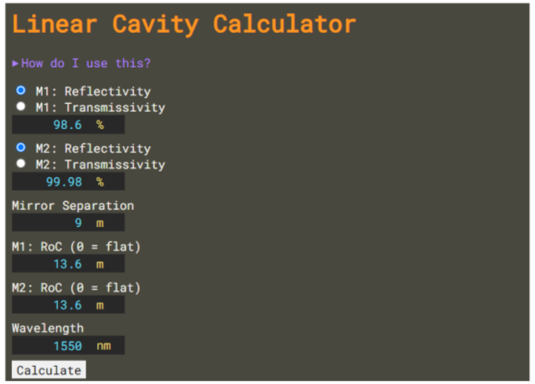
$$\psi_{RT} = 2\arccos\left(\text{sign(B)}\sqrt{\frac{A+D+2}{4}}\right),$$

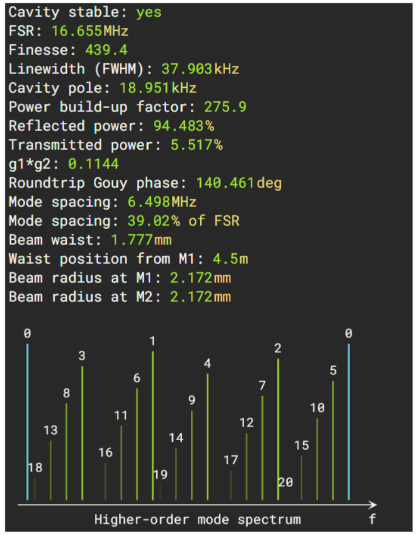
$$\psi_{RT}(g) = 2\arccos\left(\text{sign(B)}\sqrt{g}\right).$$

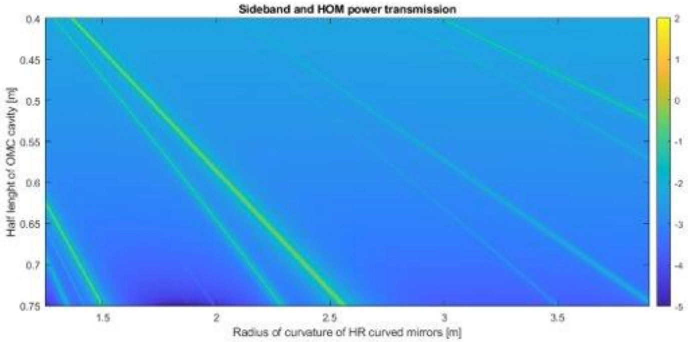


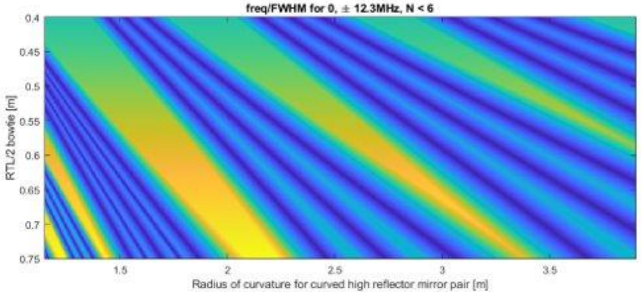
Patimisco et al.
https://doi.org/10.1016/j.sna.2017.10.005

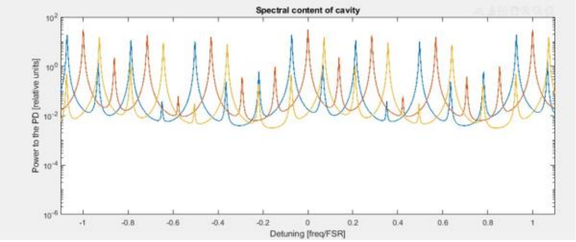
Initial selection of parameters workflow

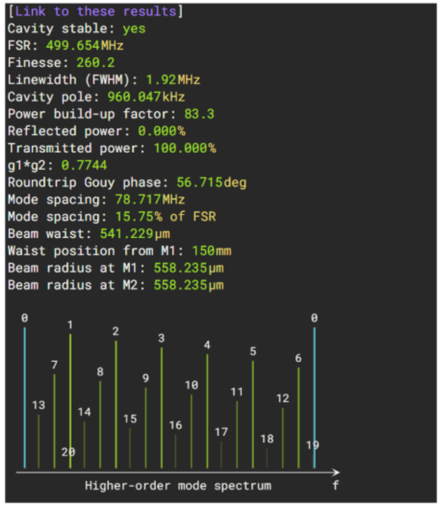


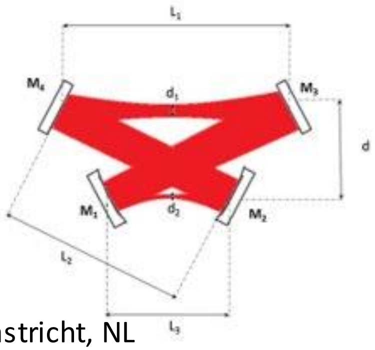




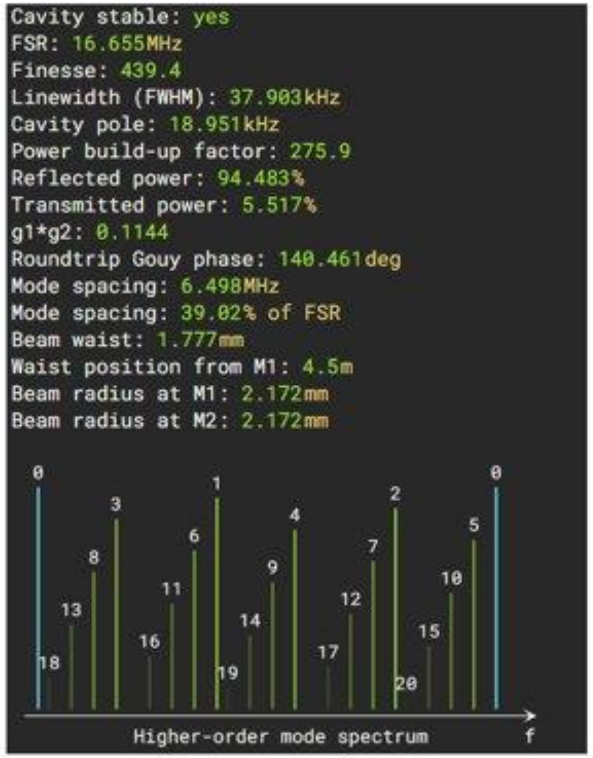


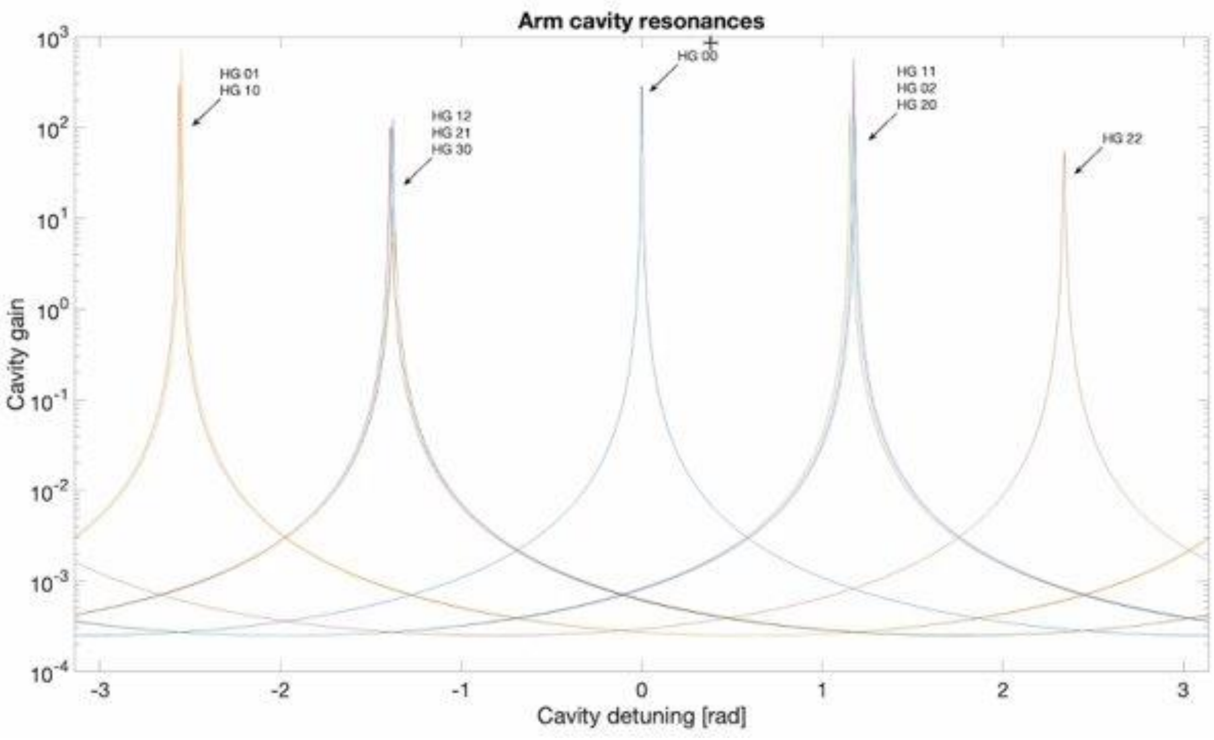






How to make this more quantitative and fine grained?
Use modeling of complete ET Pf Interferometer arm in OSCAR





Daniela's latest OSCAR calculation for one arm of ET Pf

What is next? The point of this entire talk: Design and simulation from a point of view of manufacturing and university R&D affiliated company

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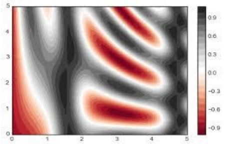
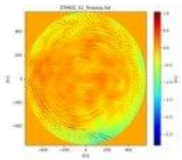
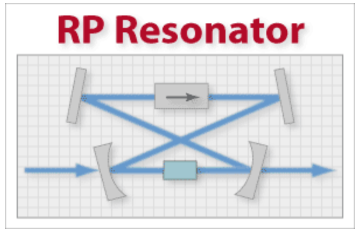
Simulation loop of OMC development

Dedicated code (S. Topic)



Import mirror maps if any, Analyse (A. Green's Zernike code)

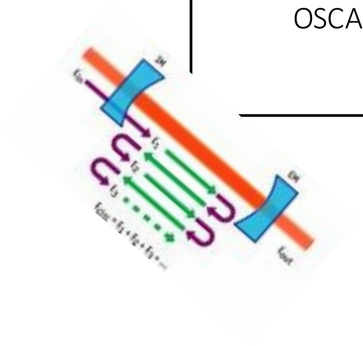




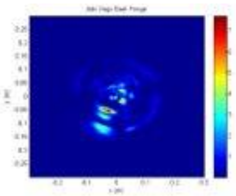
LIGHTTRANS

Virtual Lab

OSCAR



Finesse



First Time Right
First Time right+

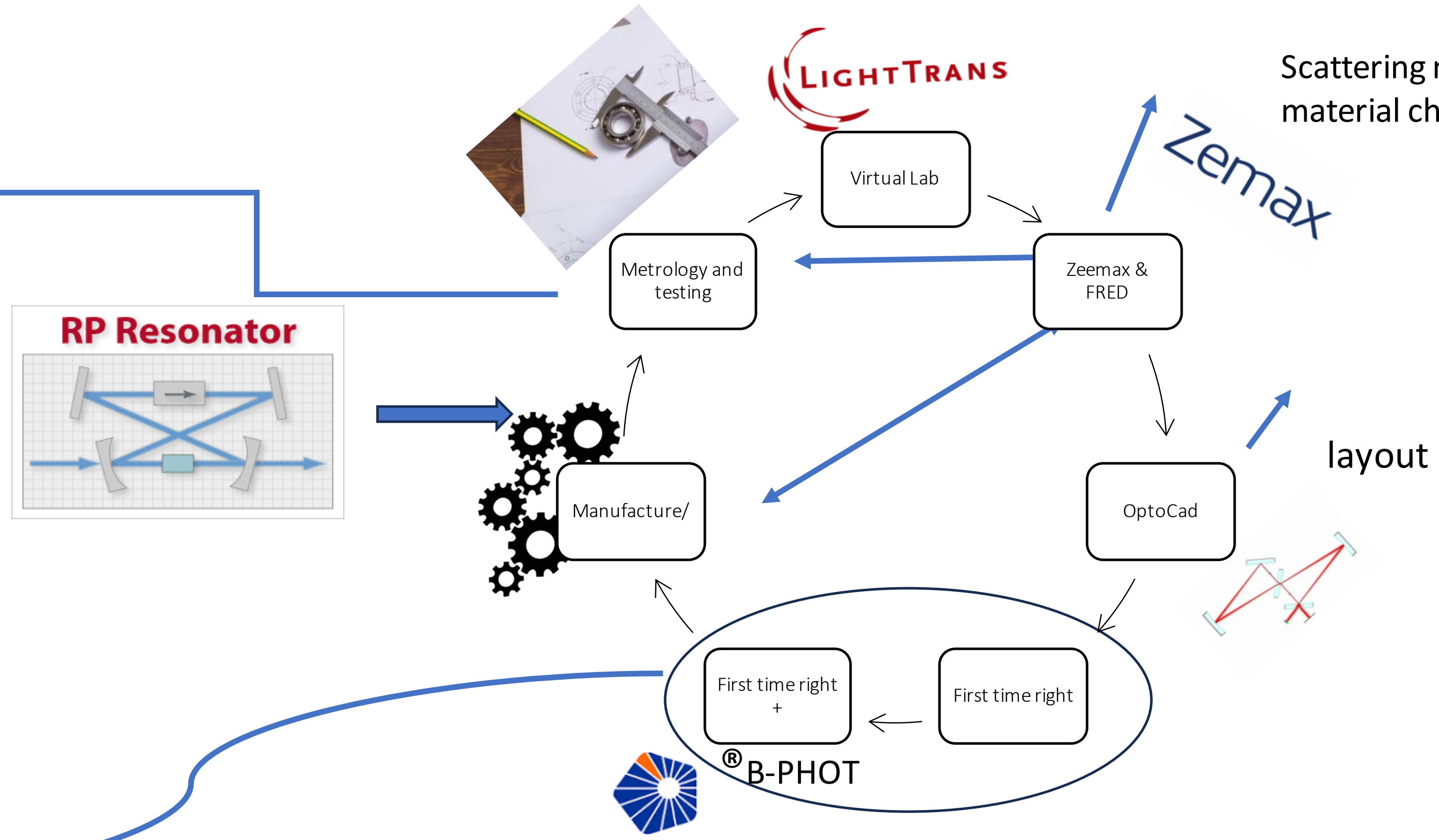
Adjustment of spherical surface mirrors into freeform to cancel astigmatism with freeform shape via appropriately weighted Zernike components – wave optics

JsCav and input IFO **arm spectrum** calculations in OSCAR/Finesse + ABCD parameter extraction

Production loop of OMC development

Measured shape to simulations that import mirror maps as they are

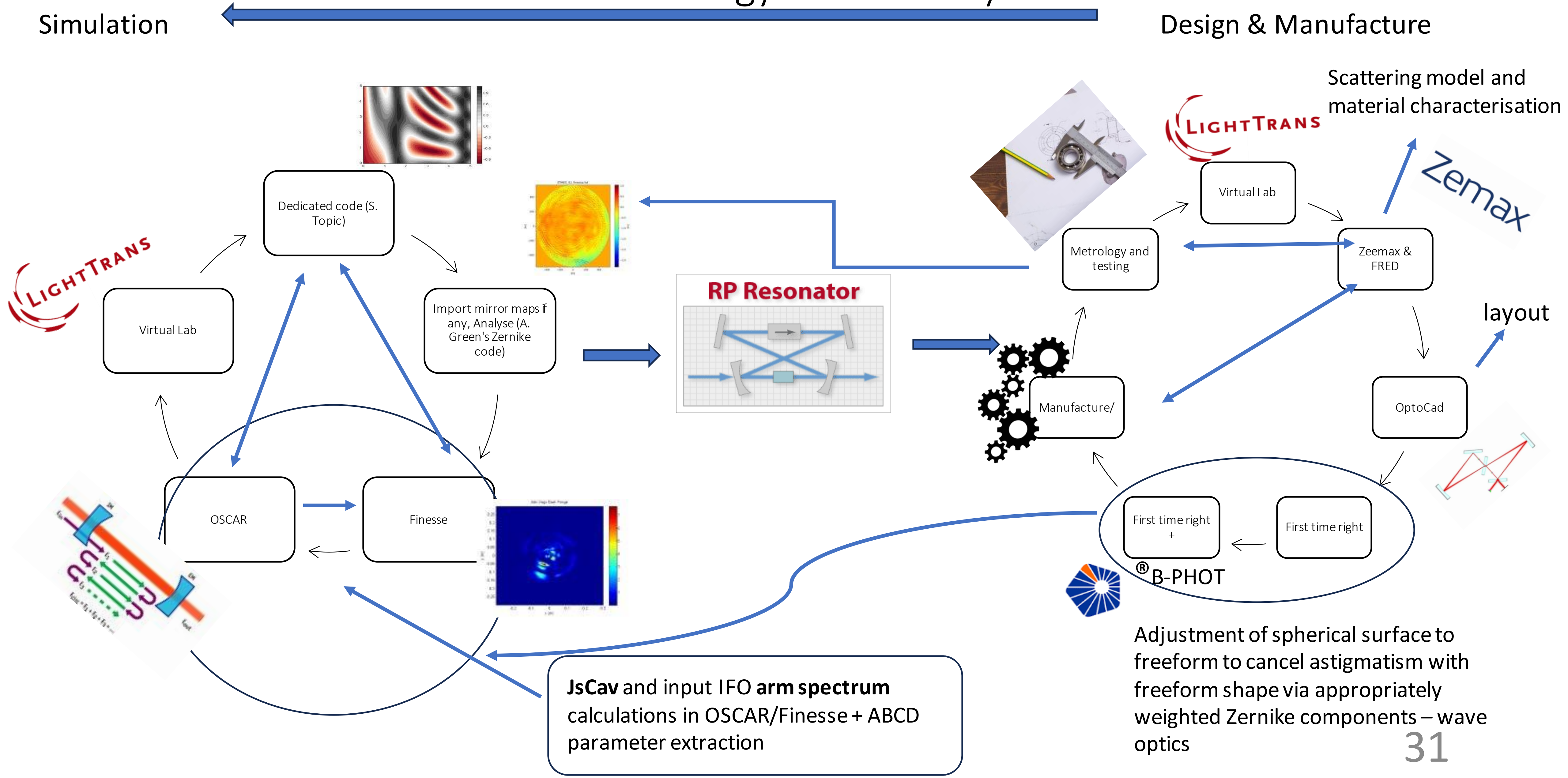
Scattering model and material characterization



Adjusted freef-om shape to simulations that import mirror maps

Adjustment of spherical surface to freeform to cancel astigmatism with freeform shape via appropriately weighted Zernike components – wave optics

Complete proposed workflow for designing, production and metrology of 3G ready OMC



To put it in words

Use **JsCav** to identify Interferometer HOM output so to tune the OMC away from the closest mode to the fundamental

Derive cavity parameters AND CAVITY CONTENT from **custom made modal power redistribution code – MPRC**

Simulate in **Finesse** - Fast prototyping and preliminary qualitative benchmarking

Simulate in **OSCAR**   - compare cavity content to the custom made code and identify the modes present - quantify effect of astigmatism etc. Use to crosscheck custom made code and Finesse

Set up aforementioned bowtie cavity in **RP Resonator** for purposes of croschecking, giving graphical schematic and a output file that supports absolute physical coordinates.

Simulate in **VL** - import absolute file from RP resonator for optimization and detailed examination of cavity static fields. Absolute coordinates and optimised configuration output to absolute physical file format suitable for CAD.

Get input file for **Zemax** and **ASAP/FRED (**from RP) - for physical coordinates, detailed ray propagation and scattering

From **Zemax** output components and coordinates to **OptoCad** - absolute breadboard placement

From **Zemax** output to CAM file and produce prototype

Measure mirror maps on Zygo. Use **Zernike maps code** to decompose and analyse them. Import mirror maps to F**inesse, OSCAR** and **VL** and simulate OMC. Simulate cavity content. Derive merit function. Send to **FTR** for optimisation. Itterate!

We have similar flowcharts for Mode matching telescope and for FD squeezing filter cavity.

But this is by far NOT set in stone but just a sketch and a proposal.

What is necessary is active participation of simulation/design/production community.

~~Thank You for attention~~! Become a software ecosystem contributor

General introduction 1: Gausian Beams and parametiric description

q_0: the *Gaussian beam parameter*. It is defined as:

$$\frac{1}{q(z)} = \frac{1}{R_C(z)} - \mathrm{i}\,\frac{\lambda}{\pi w^2(z)},$$

and can also be written as:

$$q(z) = \mathrm{i}\, z_\mathrm{R} + z - z_0 = q_0 + z - z_0, \qquad \text{where} \qquad q_0 = \mathrm{i}\, z_\mathrm{R}.$$

$$u(x,y,z) = \frac{1}{q(z)} \exp\left(-\mathrm{i}\, k \frac{x^2+y^2}{2q(z)}\right).$$

The beam size and radius of curvature can also be written in terms of the beam parameter q:

$$w^2(z) = \frac{\lambda}{\pi} \frac{|q|^2}{\mathrm{Im}\{q\}},$$

$$R_C(z) = \frac{|q|^2}{\mathrm{Re}\{q\}}.$$

$$E(x,y,z) = E_0 u_{00} \exp(-\mathrm{i}\, kz) = E_0 \left(\frac{1}{R_C(z)} - \mathrm{i}\,\frac{\lambda}{\pi w^2(z)}\right) \cdot \exp\left(-\mathrm{i}\, k \frac{x^2+y^2}{2R_C(z)} - \frac{x^2+y^2}{w^2(z)} - \mathrm{i}\, kz\right).$$

$$z_\mathrm{R} = \frac{\pi w_0^2}{\lambda}. \qquad w(z) = w_0 \sqrt{1 + \left(\frac{z-z_0}{z_\mathrm{R}}\right)^2}. \qquad w(z) \approx w_0 \frac{z}{z_\mathrm{R}} = \frac{z\lambda}{\pi \omega_0}.$$

$R_C \approx \infty,$	$z - z_0 \ll z_\mathrm{R}$	(beam waist)
$R_C \approx z,$	$z \gg z_\mathrm{R},\ z_0$	(far field)
$R_C = 2z_\mathrm{R},$	$z - z_0 = z_\mathrm{R}$	(maximum curvature)

General introduction 2: Hermite-Gaus HOM's and s & t Guoy shift

$$u_{\mathrm{nm}}(x,y,z) = \left(2^{n+m-1}n!m!\pi\right)^{-1/2} \frac{1}{w(z)} \exp\left(\mathrm{i}\,(n+m+1)\Psi(z)\right) \times H_n\left(\frac{\sqrt{2}x}{w(z)}\right) H_m\left(\frac{\sqrt{2}y}{w(z)}\right) \exp\left(-\mathrm{i}\,\frac{k(x^2+y^2)}{2R_C(z)} - \frac{x^2+y^2}{w^2(z)}\right),$$

The Gouy phase can be written as:

$$\Psi(z) = \arctan\left(\frac{z-z_0}{z_\mathrm{R}}\right) = \Psi(z) = \arctan\left(\frac{\mathrm{Re}\{q\}}{\mathrm{Im}\{q\}}\right).$$

Compared to a plane wave, the phase lag φ of a Hermite-Gauss mode

$$\varphi = (n+m+1)\Psi(z).$$

$$\varphi = \left(n+\frac{1}{2}\right)\Psi_t(z) + \left(m+\frac{1}{2}\right)\Psi_s(z),$$

General Introduction3: Computing Gouy phase roundtrip shift through arbitrary cavity with ABCD matrices – example of a bowtie OMC

$$\frac{q_2}{n_2} = \frac{A\frac{q_1}{n_1} + B}{C\frac{q_1}{n_1} + D},$$

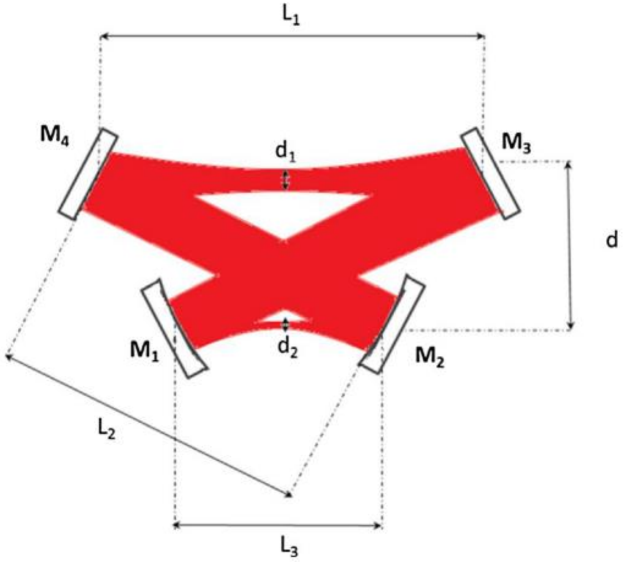
with the coefficient matrix

$$M = \begin{pmatrix} A & B \\ C & D \end{pmatrix},$$

$$\psi_{\mathrm{RT}} = 2\arccos\left(\mathrm{sign}(\mathrm{B})\sqrt{\frac{\mathrm{A}+\mathrm{D}+2}{4}}\right),$$

$$\psi_{\mathrm{RT}}(g) = 2\arccos\left(\mathrm{sign}(\mathrm{B})\sqrt{\mathrm{g}}\right).$$

$$\delta f = \frac{\psi_{\mathrm{RT}}}{2\pi}\mathrm{FSR}.$$



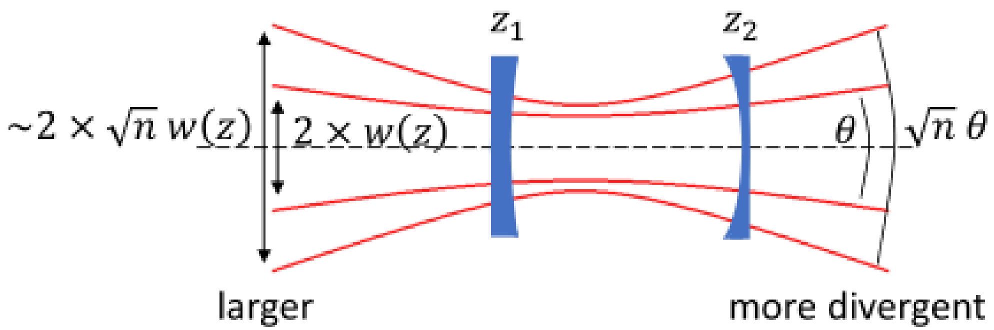
$$\begin{pmatrix} A_1 & B_1 \\ C_1 & D_1 \end{pmatrix} = \begin{pmatrix} 1 & \frac{L_1}{2} \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -\frac{2}{R} & 1 \end{pmatrix} \begin{pmatrix} 1 & L_3+2L_2 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -\frac{2}{R} & 1 \end{pmatrix} \begin{pmatrix} 1 & \frac{L_1}{2} \\ 0 & 1 \end{pmatrix}$$

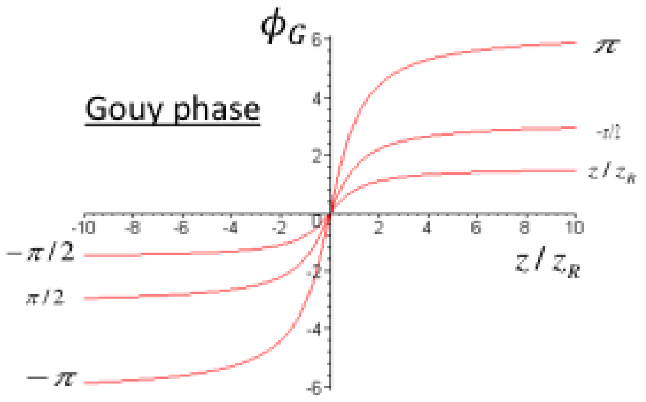
$$\frac{1}{q_i} = -\frac{A_i - D_i}{2B_i} - j\frac{\sqrt{1-A_i^2}}{B}$$

$$d_i = \sqrt{\frac{\lambda B_i}{\pi\sqrt{1-A_i^2}}}$$

Patimisco et al.
https://doi.org/10.1016/j.sna.2017.10.005

General introductio 4: Guoy phase of Gaussian beams and HOM's





$$\phi(z_2) - \phi(z_1) = \frac{2\pi(z_2 - z_1)}{c}\nu_{N_T,s} + (N_T + 1)\big(\phi_G(z_2) - \phi_G(z_1)\big) = s \times \pi$$

N_T : Mode total order