EGO - Virgo

# A Novel Non-Sequential 3D Gaussian Beam Tracer: Theia

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**What is `theia`?**

- Synthesis of existing Gaussian optics simulation tools (OptoCAD, gtrace, IfoCad)
- + enhanced flexibility → Scripting
- + enhanced user interface → 3D visualization and navigation
- + enhanced user environment → support and extensibility
- + specific aims in optics design

**What are the specific aims?**

- Ghost beam hunting
- Large-scale optical benches

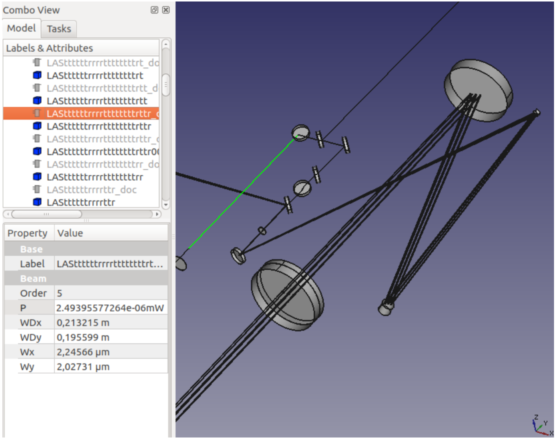



Figure: Working environment of `theia`

# Overview

# Overview

**Scope of theia:** Non-sequential 3D Gaussian beam tracer *and* visualization

| **No** | **Yes** (July 14th) | **Not yet** | **Extensions** |
|---|---|---|---|
| Higher order modes | 3D general astigmatic Gaussian beams | All 2nd order surfaces | Polarization |
| Grating surfaces | Spherical surfaces (mirrors, lenses) | High-level 3D visualization | Surface action specification |
| Response in GW environment | {Non-, }sequential tracing | Beam tree navigation interface (and transverse section inspection) | 2-way communication with CAD |
| | Low-level 3D visualization | Interferences | |
| | | Cavities | |
| | | Beam clipping | |

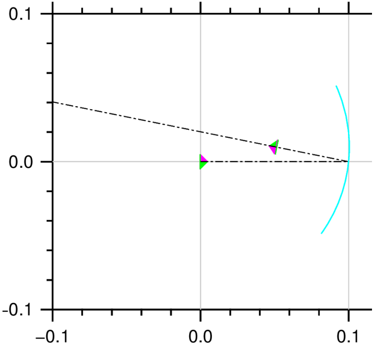
Table: The functionalities of theia v0.1.1

**Approximations:**

- Geometrical optics: none
- Gaussian data: ROC(beam) $\gg$ ROC(surface) (+ paraxial)

**Test cases:**

- 2D: confronted with OptoCAD
- 3D: comparison with experimental data
- See tutorial files in project



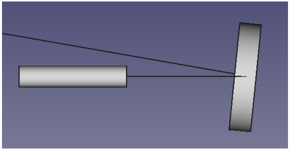
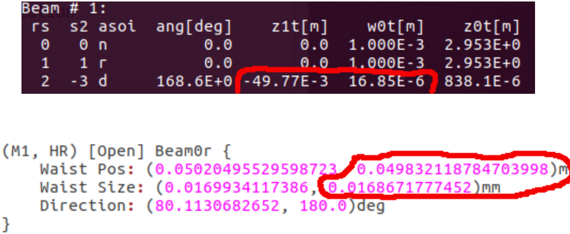



Figure: Simple setup for Gaussian optics testing (*top*: OptoCAD, *bottom*: theia).



Beam # 1:

| rs | s2 | asoi | ang[deg] | z1t[m] | w0t[m] | z0t[m] |
|---|---|---|---|---|---|---|
| 0 | 0 | n | 0.0 | 0.0 | 1.000E-3 | 2.953E+0 |
| 1 | 1 | r | 0.0 | 0.0 | 1.000E-3 | 2.953E+0 |
| 2 | -3 | d | 168.6E+0 | -49.77E-3 | 16.85E-6 | 838.1E-6 |

```
(M1, HR) [Open] Beam0r {
    Waist Pos: (0.0502049552959872З, 0.0498321187847039 98)m
    Waist Size: (0.0169934117386, 0.0168671777452)mm
    Direction: (80.1130682652, 180.0)deg
}
```

Figure: Results comparison between OptoCAD (*top*) and theia (*bottom*).

**OptoCAD and theia in agreement:**

- Size of waist: $\leq 0.1\%$
- Position of waist: $\leq 0.1\%$

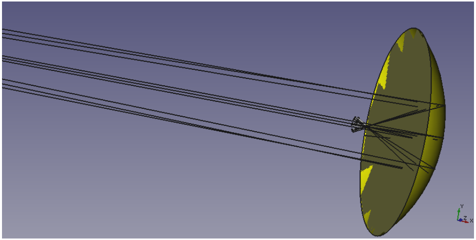



Figure: Interaction of a pencil of beams with a spherical reflecting surface

- Test against geometrical optics results
- Test against experimental results

# Overview

Algorithms + Data Structures = Programs

**What low-level features allow the ghost beam hunting functionality?**

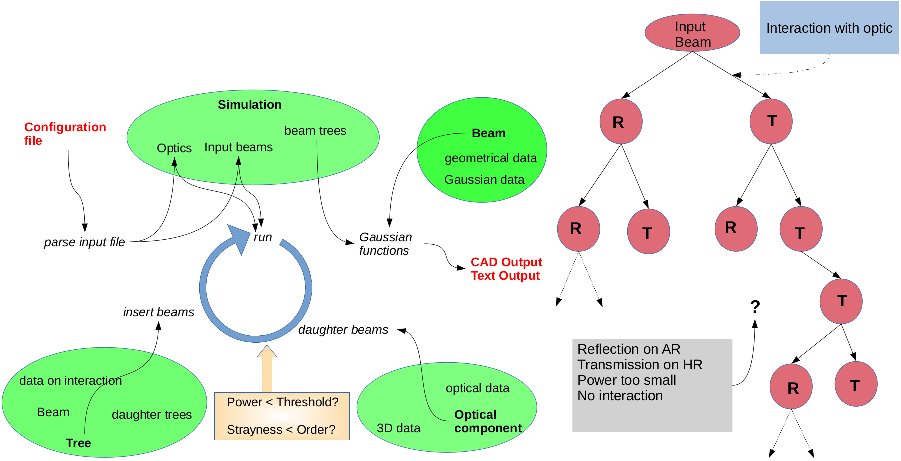



Figure: *Left*: the algorithm implemented in theia, *right*: the beam tree data structure.

# Operation of theia

## User interface

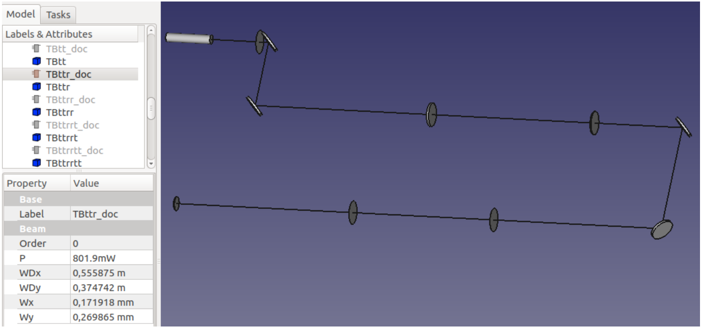
### Text input

```
#Threshold and order each on their own line
order = 1
threshold = 1.*mW

# input beam
#bm Wx    Wy    WDistx   WDisty   Wl   P    X    Y    Z    Theta    Phi Alpha    Name    Re
bm 0.045*mm, 0.094*mm, -43*mm,  -45.0*mm,   1064*nm,    1*W, Y = 0*m, Z = 0.,

# thin lens (X,Y,Z is the center of the thin lens)
#th X    Y    Z    Theta    Phi Focal    Diameter    R    T    KeepI    Name    Ref
th 11*cm, 0, 0, 90 * deg, arccos(-1.), sqrt(144)*cm, 5*cm, 0.1, 0.9, True, Ref = 'L1'
th 53*cm, -15*cm, 0, 90*deg, 180 * deg, -150*mm, 5*cm, Ref = 'L2'
th 90*cm, -15*cm, 0, 90*deg, 180 * deg, -300*mm, 5*cm, Ref = 'L3'
```

### Text output

```
(M2, HR) 0.3999999999m (L2, HR) TBttrr {
    Waist Pos: (0.22474241537119777, 0.40587482437740047)m
    Waist Size: (0.269864950223, 0.171918229273)mm
    Direction: (90.0, -1.90833280888e-14)deg
}
```

### 3D CAD output



# Overview

`http://theia.hopto.org:56000`

- Quick start guide
- User documentation
- API documentation
- Tutorials
- Releases
- Contact with maintainer
- Access to git repo

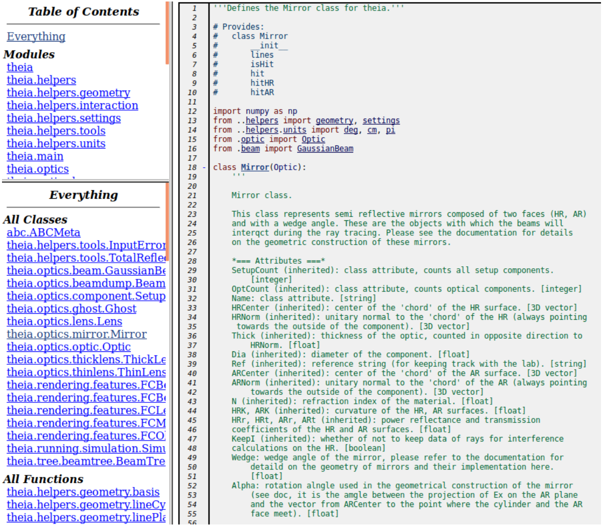



Figure: `theia` online API documentation

# Overview

1. Scope and validation of theia
2. Operation of theia
3. The extensive user environment
4. Quick tutorial

- Typical telescope/cavity setup, used as a test case for experimental validation
- Order 1 simulation for ghost beam hunting: **Will transmitted beams interfere with PD?**

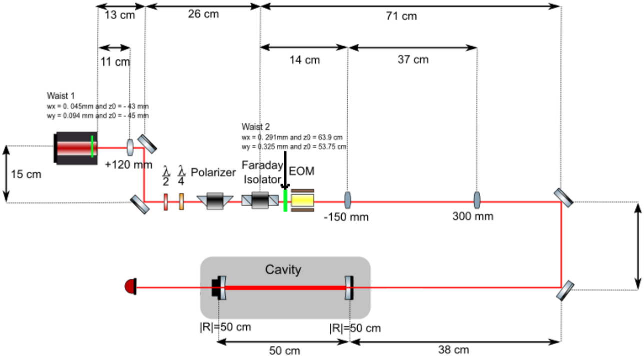



Figure: Typical simulation setup (courtesy Léa Lhopital, Optics Group)

| **Plane** | Sagittal | Tangential |
|---|---|---|
| **Exp.** | 260 $\mu$m @ 22 cm | 170 $\mu$m @ 41 cm |
| **Sim.** | 320 $\mu$m @ 26 cm | 290 $\mu$m @ 36 cm |

Table: Experimental and simulation data for this telescope/cavity setup (beam waist @ waist position)

**Overall agreement:**

- Size of waist: $\leq$ 50%
- Position of waist: $\leq$ 20%

- New 3D simulation tool to respond to specific aims: **Ghost beam hunting and large-scale setups**
- Next steps: **confirm test cases, implement following features, communicate** (`theia.hopto.org:56000`)

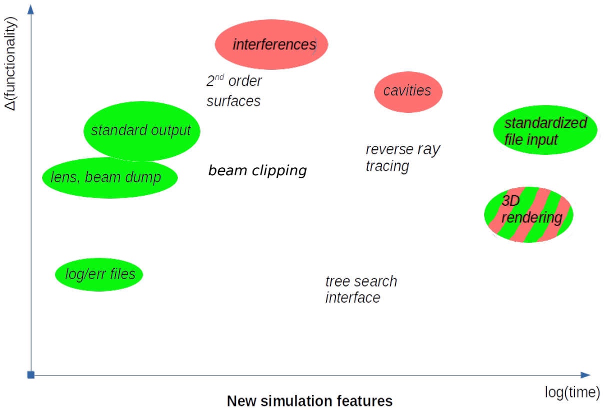



Figure: The near future of `theia`

[1] E. Kochkina, G. Wanner, D. Schmelzer, M. Tröbs, G. Heinzel: *Modeling of the General Astigmatic Gaussian Beam and its Propagation through 3D Optical Systems*, Applied Optics 24 (2013)

- Optimum placement of lens $L2$ for maximum width of transmitted beam? For position of waist?
  $\Rightarrow$ Small script


Figure: Optical setup (*left*) and Python script (*right*) for an optimization case

Setup

```
#simulation object
simu = simulation.Simulation(FName = 'optimization')
simu.LName = 'Optimizing with theia!'
simu.Order = 0
simu.Threshold = 0.5*mW
```

Optical data specification

```
#optics, the first L1 lens doesn't move
L1 = thinlens.ThinLens(X = 0*cm, Y = 0., Z = 0., Focal = 20.*cm,
            Diameter = 3.*cm, Phi = 180.*deg, Ref = 'L1')

bm = beam.userGaussianBeam(1.*mm, 1.*mm, 0., 0, 1064*nm, 1*W,
                         X = -30*cm, Phi = 0, Ref = 'Beam')

# this is a list of centers for the second lens we want to try (it is around
#70 cm = L1.X + 2*Focal to respect the 2F configuration). We're trying n
#configurations around L2.X = 50
n = 500
centers = [ 40.*cm + 2.*cm*(float(i)/n) for i in range(-n, n)]
waistSizes = []
waistPositions = []

# load beam
simu.InBeams = [bm]
```

Optimization sequence

```
#run the simulations in sequence!
for center in centers:
    dic = {'X': center, 'Y': 0., 'Z': 0., 'Focal': 20.*cm,
        'Diameter': 3.*cm, 'Theta': 90*deg, 'Phi': 180.*deg, 'Ref': 'L2'}
    simu.OptList = [L1, thinlens.ThinLens(**dic)]

    #go theia go!
    simu.run()
    output = simu.BeamTreeList[0].T.T.T.T.Root

    #save output data for plotting
    waistSizes.append(output.waistSize()[0])
    waistPositions.append(output.waistPos()[0])

simu.writeCAD()
```

Plotting

```
#plot the results
plt.figure(1)
plt.subplot(211)
plt.plot(centers, waistSizes, 'r')
plt.ylabel('waists (m)')
plt.xlabel('center of second lens (m)')
plt.subplot(212)
plt.plot(centers, waistPositions, 'g')
plt.ylabel('positions (m)')
plt.xlabel('center of second lens (m)')
plt.show()
```

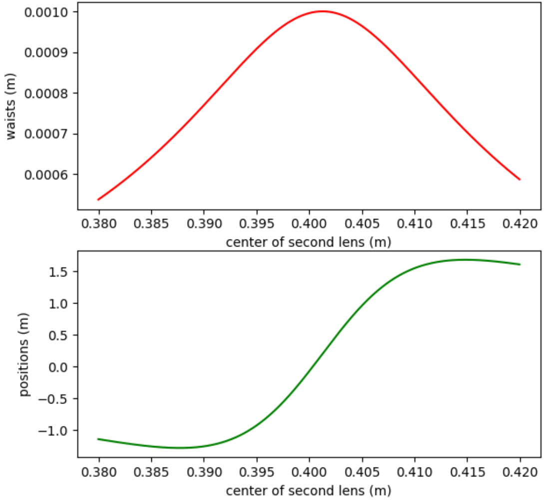



Figure: Width (*top*) and position (*bottom*) of the waist of the output beam as calculated by `theia`

- General astigmatic Gaussian beam in an orthogonal basis $(k, e_1, e_2)$:

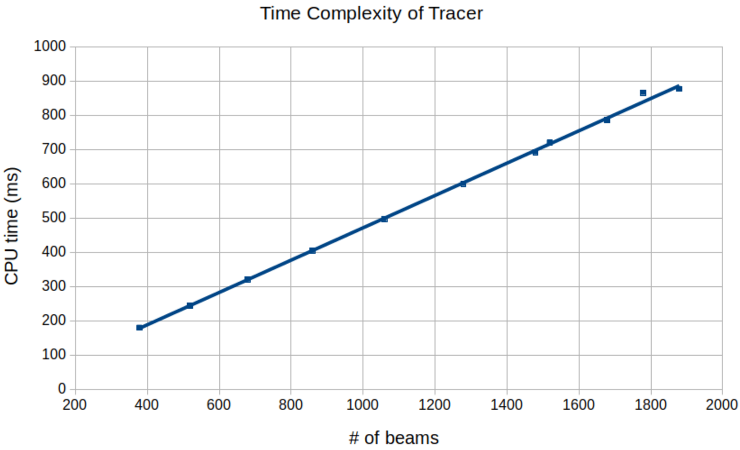
$$E(\vec{r}, t) = \exp[i\eta(z) - i\frac{k}{2}{}^t(x, y)Q(z)(x, y)]e^{i(\omega t - kz)}$$

- $(x, y)$ is the transversal coordinate in the $(e_1, e_2)$ basis, $Q$ is a symmetrical tensor:

$$\begin{pmatrix} \frac{\cos^2\theta}{q_x(z)} + \frac{\sin^2\theta}{q_y(z)} & \frac{1}{2}\sin 2\theta\left(\frac{1}{q_x(z)} - \frac{1}{q_y(z)}\right) \\ \frac{1}{2}\sin 2\theta\left(\frac{1}{q_x(z)} - \frac{1}{q_y(z)}\right) & \frac{\sin^2\theta}{q_x(z)} + \frac{\cos^2\theta}{q_y(z)} \end{pmatrix}$$

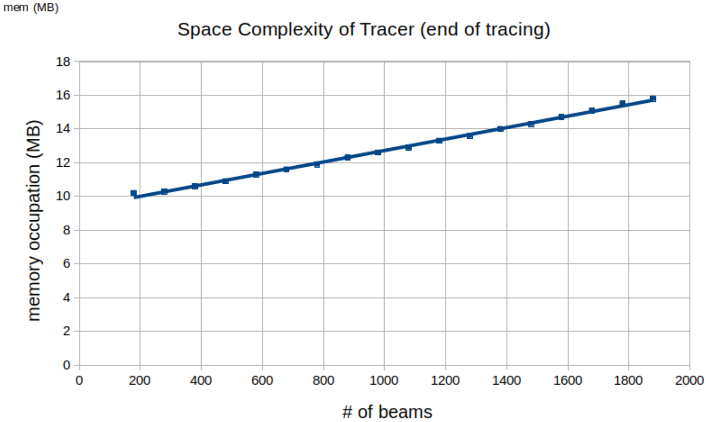
- Specification parameters: $\theta, q_{x,y} \in \mathbb{C}$, $(e_1, e_2)$ basis.
- **Approximations:** ROC(beam) $\gg$ ROC(surface) (+ paraxial)
- Geometric optics: no approximation

# Benchmarking: time (i7/8GB)




- CPU = 0.47ms × (# beams) ($R^2 = 99.95\%$)

# Benchmarking: space (i7/8GB)




- Mem. = 9,3MB + 3,4kB/beam ($R^2$ = 99.76%)