E2E's Physics tools

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E2E school, LLO

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LIGO, Caltech

Tools:

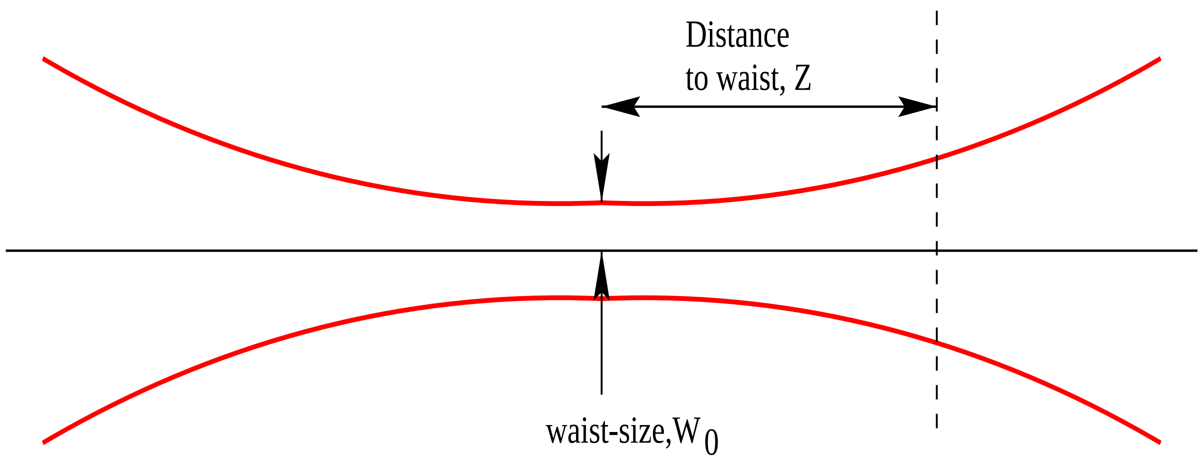
- Optics
- Electronics
- Mechanical
- Mathematical functions
- Data generation and output

Optics

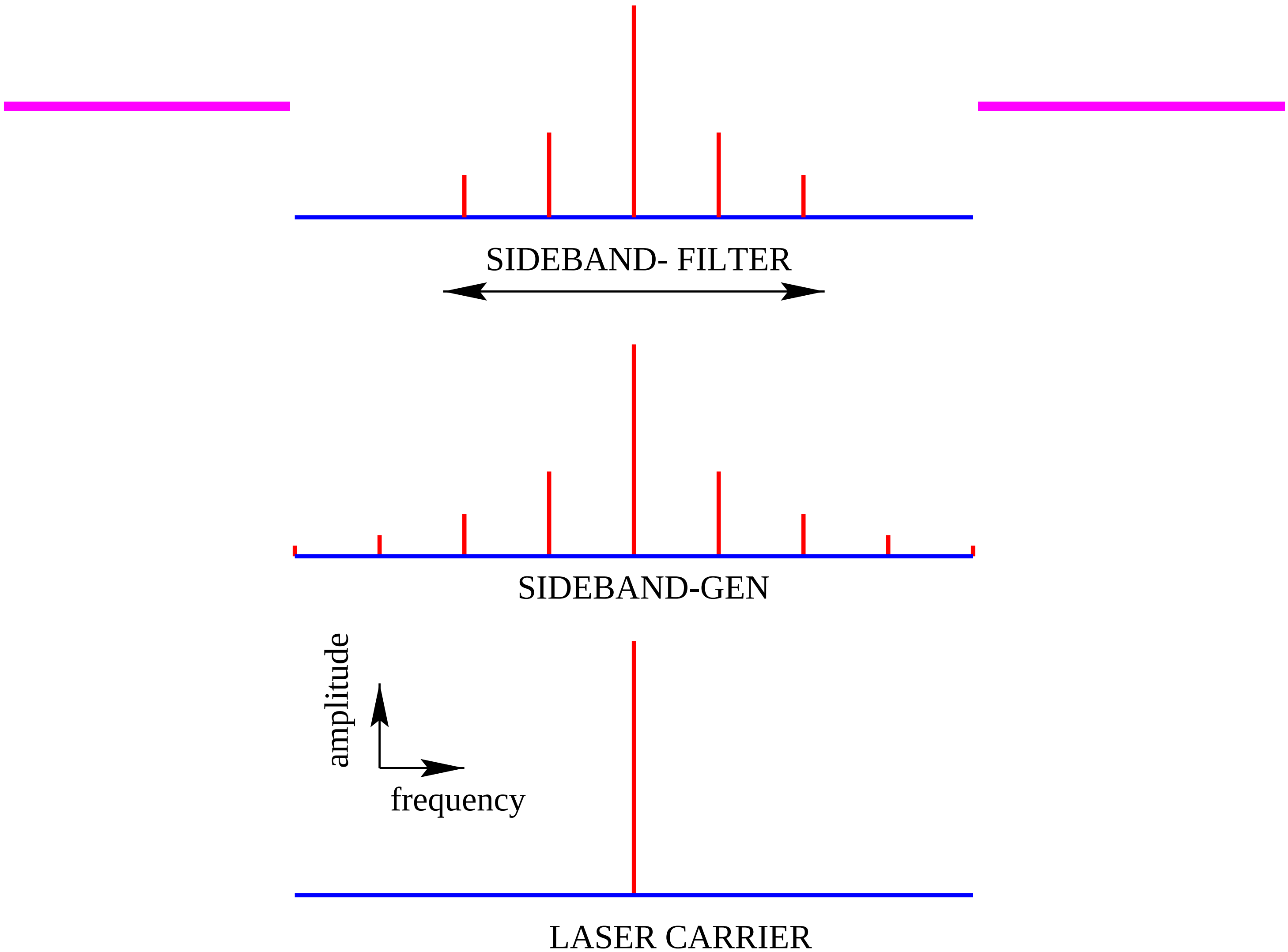
- Laser & Field
- Field operations
  - » modulator, sideband-gen, sideband-filter, freq-shifter
- Beam operations
  - » propagator,shifter,wiggler
- Mirror, lens, telescope
- Summation cavities
  - » Fabry-Perot, triangular, recycling cavity,
- Measurements:
  - » power-meter, photodetector,

Laser
(The “field-gen” module)

- Laser (a la “field-gen”) generates field at a fixed central frequency
- It could be plane-wave or a Gaussian beam
- If it’s a Gaussian beam, its basis (distance to waist and waist-size) needs to be specified
- amplitude of different spatial modes (in Hermite-Gaussian basis) can be specified



Sideband generator

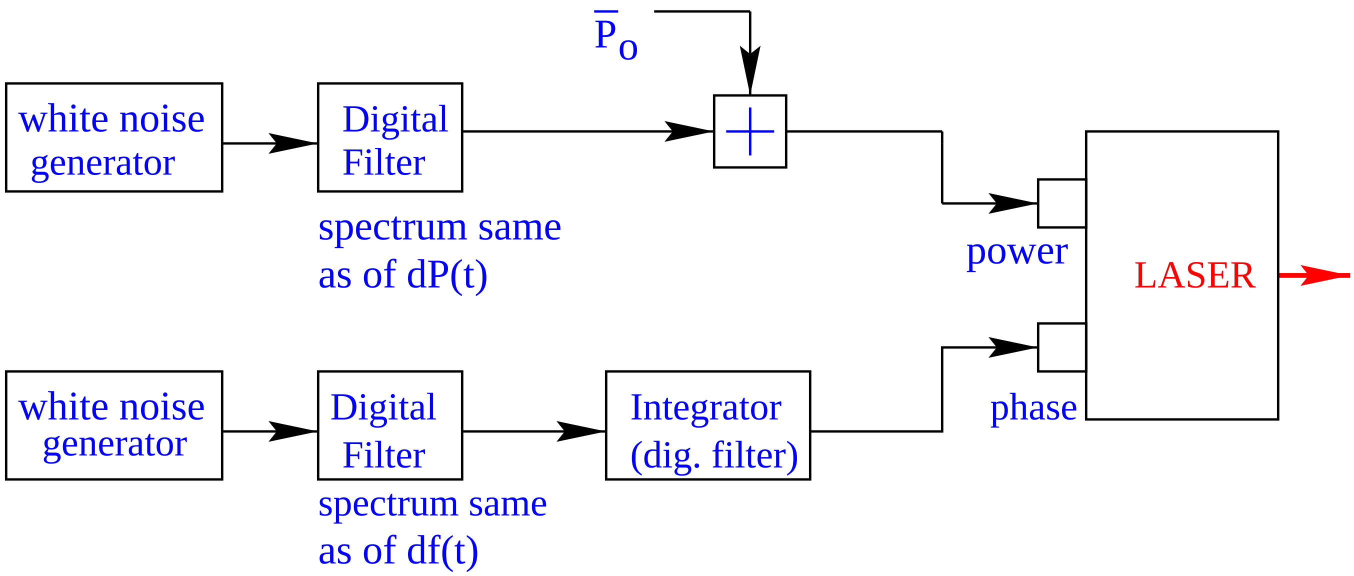


›› "Sideband-gen":

$$E_{out} = E_{in} \cdot \mathrm{Exp}(i\Gamma_{\varphi}\sin(\Omega t)) \cdot \mathrm{Exp}(\Gamma_{amp}\sin(\Omega t))$$

$$E_{out} \approx E_{in} \cdot \sum_{n=-N}^{N} \left(\sum_{i=-N}^{N} (-i)^{n-i} \cdot J_i(\Gamma_{\varphi}) \cdot I_{n-i}(\Gamma_{amp}) \right) \cdot \exp(in\Omega t)$$

Phase and Frequency noise
(as input to Laser)



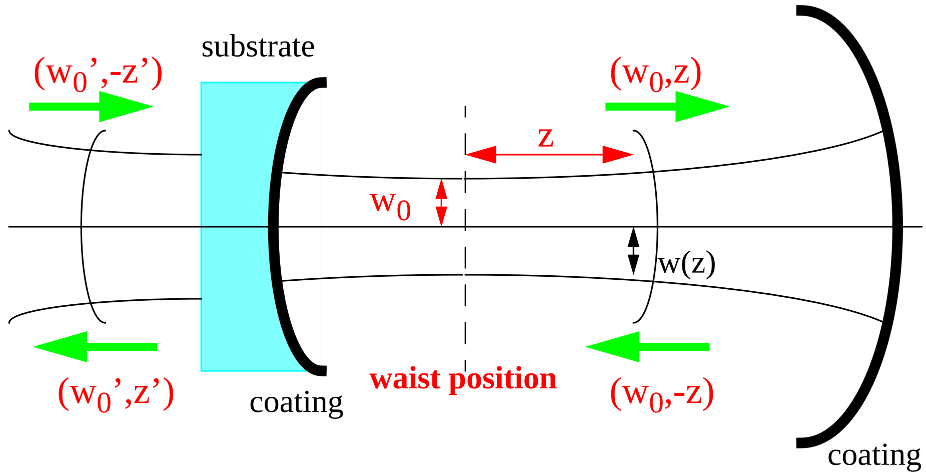
- **Note:** All frequencies of carrier and sidebands are constants during the simulation
- implementation of frquency noise:

$$\phi(t) = \int_0^t \omega(t)dt = \omega_0 \cdot t + \int_0^t \delta\omega(t)$$

- At any other point use "Field-modulator" module

out = in * (1+del_amp) * exp(i*phi)

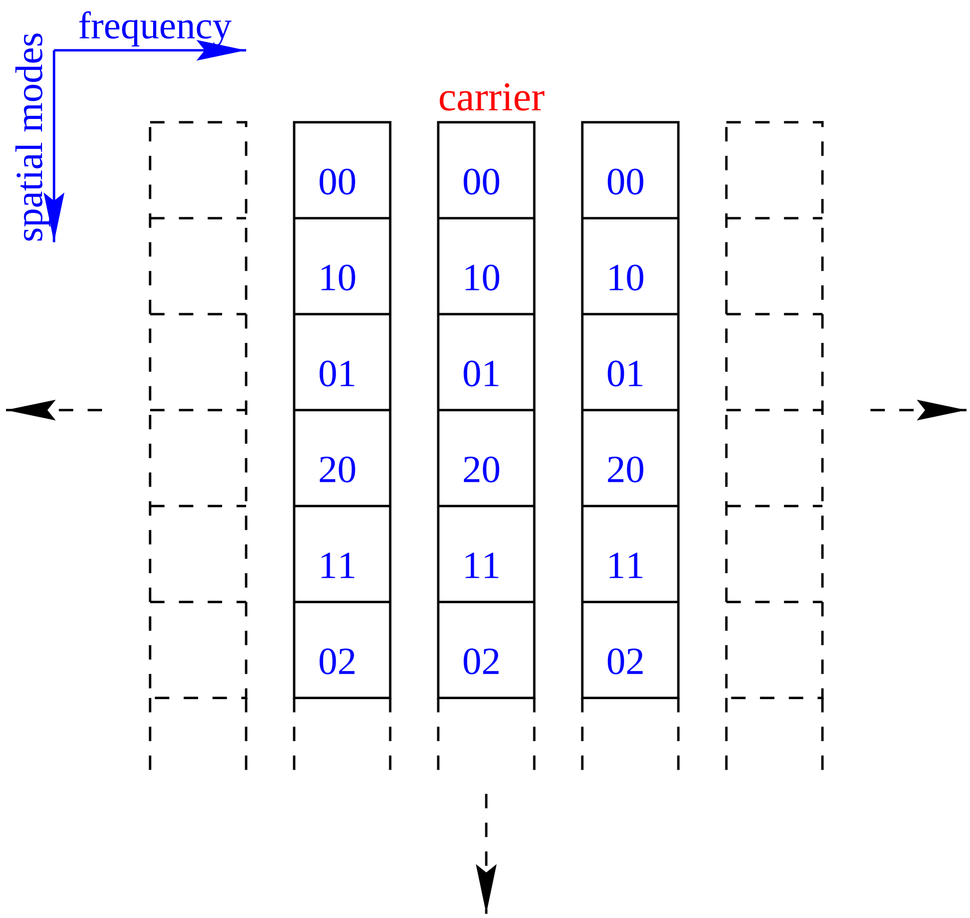
Time-domain modal model



- Field carries two modal info: waist-size, dist-to-waist
- Tilt, shift, curvature mismatch are treated using mode decomposition matrix
- Modal basis changes
  - after passing thru lens/curved mirror
  - on reflection at an angle from a curved mirror

contents of ‘Field’

- In E2E modes upto 4th order (15 modes) can be considered



- a “power-meter” module can measure power
  - for any mode of any frequency
  - For one freq: total power of all modes or modes of a certain order

Photodetector

- Pd-demod:
  - » photodetector+demodulation+low_pass_filter
  - » shape

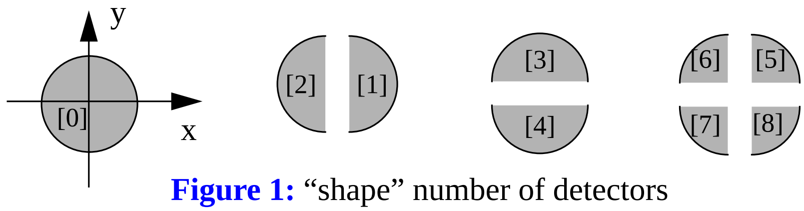


Figure 1: "shape" number of detectors

  - » "detmap"

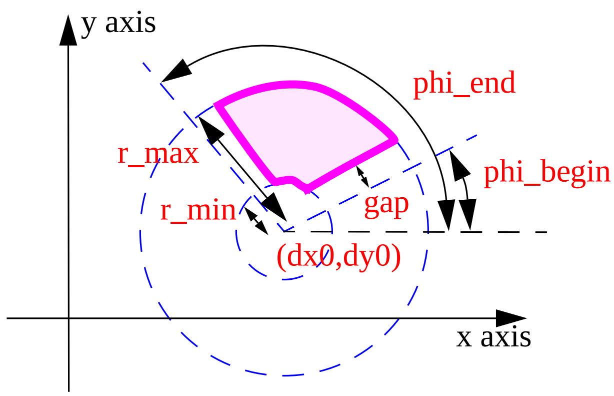


Figure 2: Specification of a detector

  - » ready-made boxes

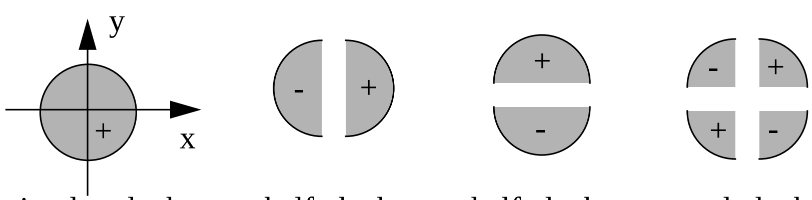


Figure 3: detector boxes

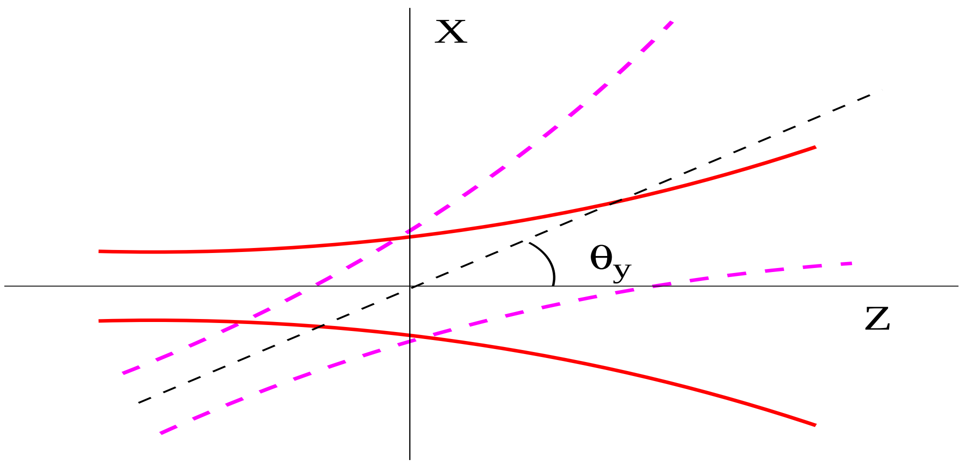
misalignment effects
(in Hermite-Gaussian basis)

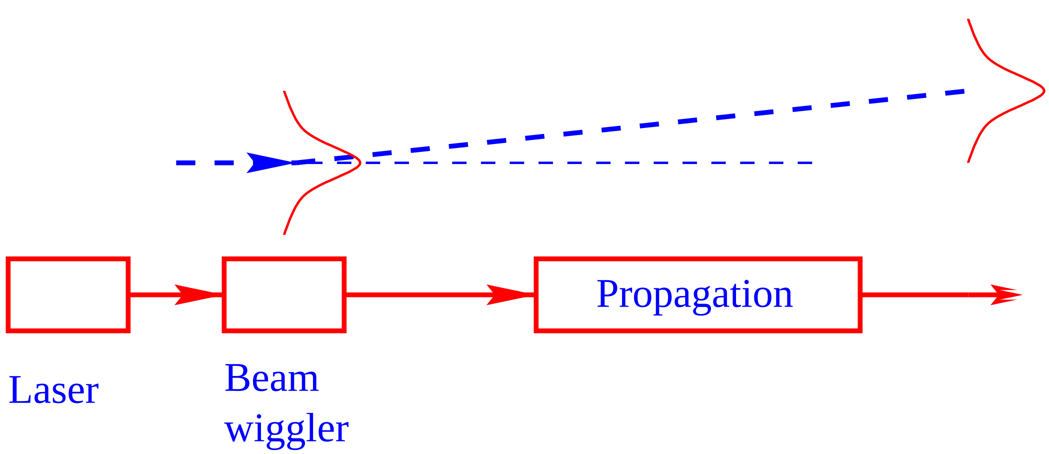
- Initial beam : k - mode no. ; w - waist

$$AU_0$$

- 'Beam-wiggler' : deviation (p) of beam by an angle

$$A\left[U_0 + jp\frac{kw}{\sqrt{2\pi}}U_1\right]$$

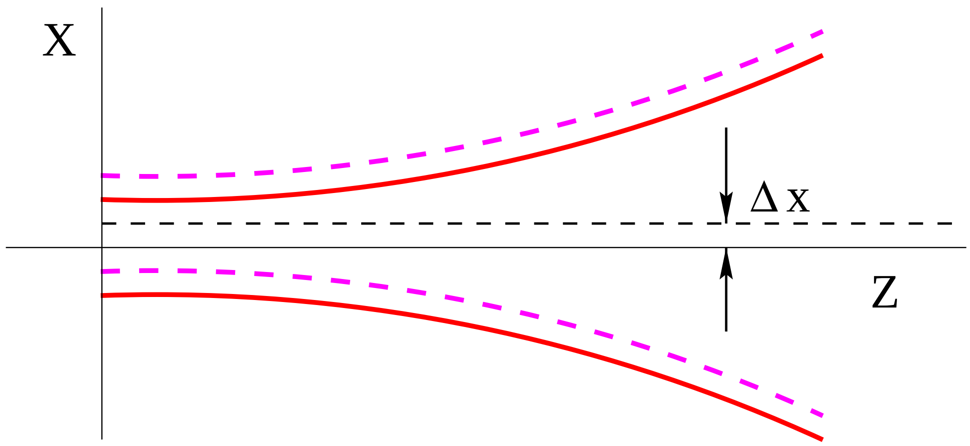




misalignment effects

- Beam-shifter : lateral displacement (d)

$$A\left[U_0 + \left(\frac{2}{\pi}\right)^{1/2}\frac{d}{w}U_1\right]$$



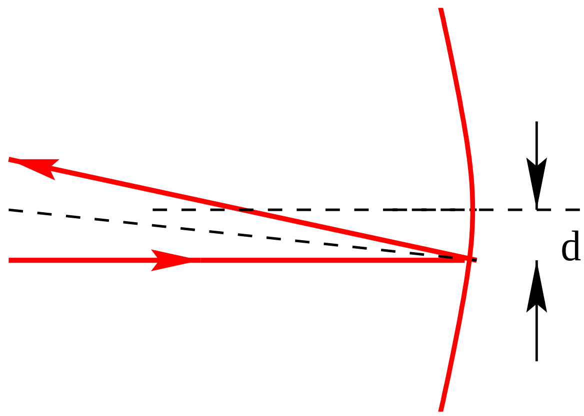
misalignment effects

in Mirror

- mirror tilts : rotation (r) by an angle (pitch or yaw)

$$A\left[U_0 + jr\frac{kw}{\sqrt{2\pi}}U_1\right]$$

- mirror's lateral shift : eqv. to rotation



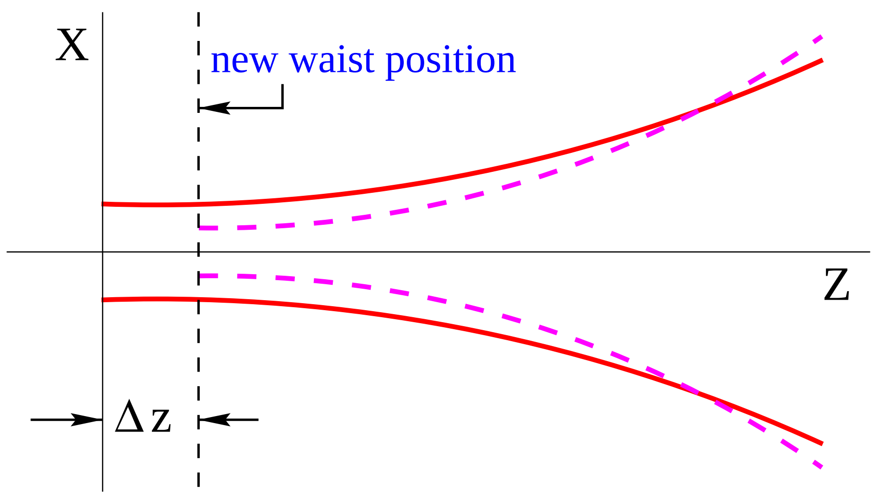
Mode Mismatch

- Mode mismatch:
  - **change in waist size**
  - **shift in beam position**
- Waist-position mismatch (b) :

$$A\left[U_0 + j\frac{b}{2kw^2}\{U_0 + U_2\}\right]$$

- Waist-size mismatch (s) :

$$A\left[U_0 + \frac{s}{2w}U_2\right]$$



Mirror
Reflection and Transmission Operations

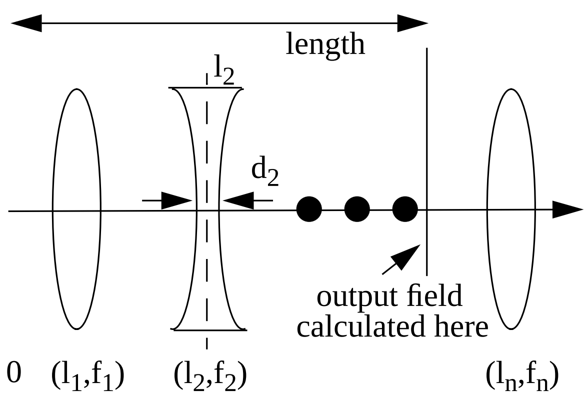
- Reflection Operation (of mirror) on ‘field’:
  - multiplication by amplitude-reflectivity with appropriate sign
  - changes in transversal modal-basis of the beam if reflected at an angle from a curved mirror
  - appropriate phase factor for small longitudinal displacement
  - a composite matrix representing small perturbations in mirror, like rotation, shift, mismatch between mirror surface and phase-front, etc.
  - parity operation which flips the beam about vertical axis

- Transmission operation (of mirror) on ‘field’:
  - multiplication by amplitude-transmissivity
  - changes in transversal modal-basis of the beam (lensing)

Propagation

(prop and telescope)

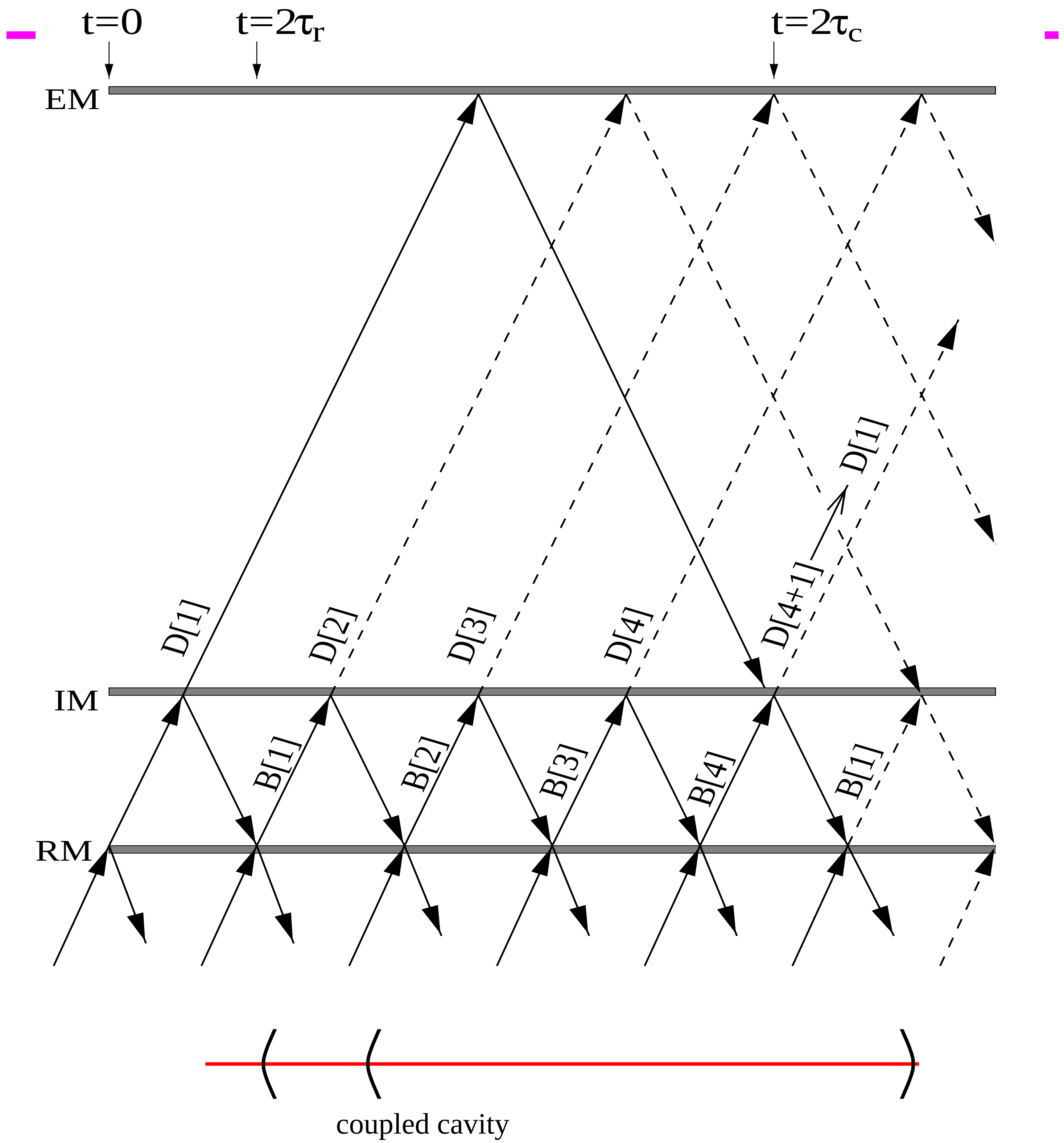
- Effects (in vacuum)
  - longitudinal phase
  - gouy phase
  - change of basis (distance to waist changes)
  - time-delay
- telescope



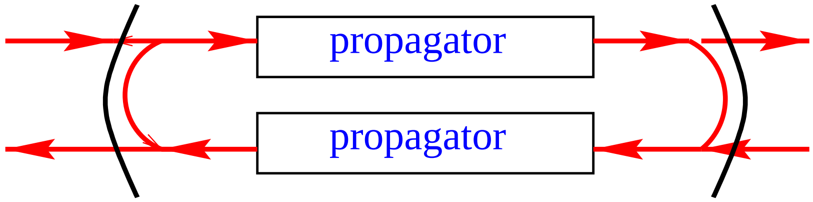
  - Prop module effects propagation thru vacuum and may or may not include time-delay (user's choice)
  - Telescope module can propagate light thru a series of lens placed in vacuum with all changes in guoy phases properly included
  - The telescope effect can also be specified by setting the basis and gouy phase information at the output instead of specifying details of lens & length

Composite Systems

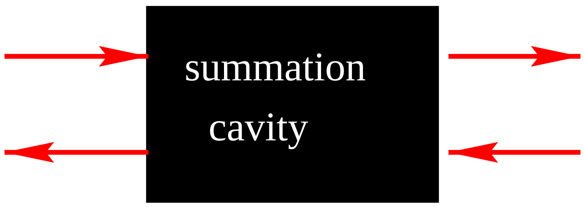
(What are *summation modules*?)



Composite Systems
(*summation modules*)



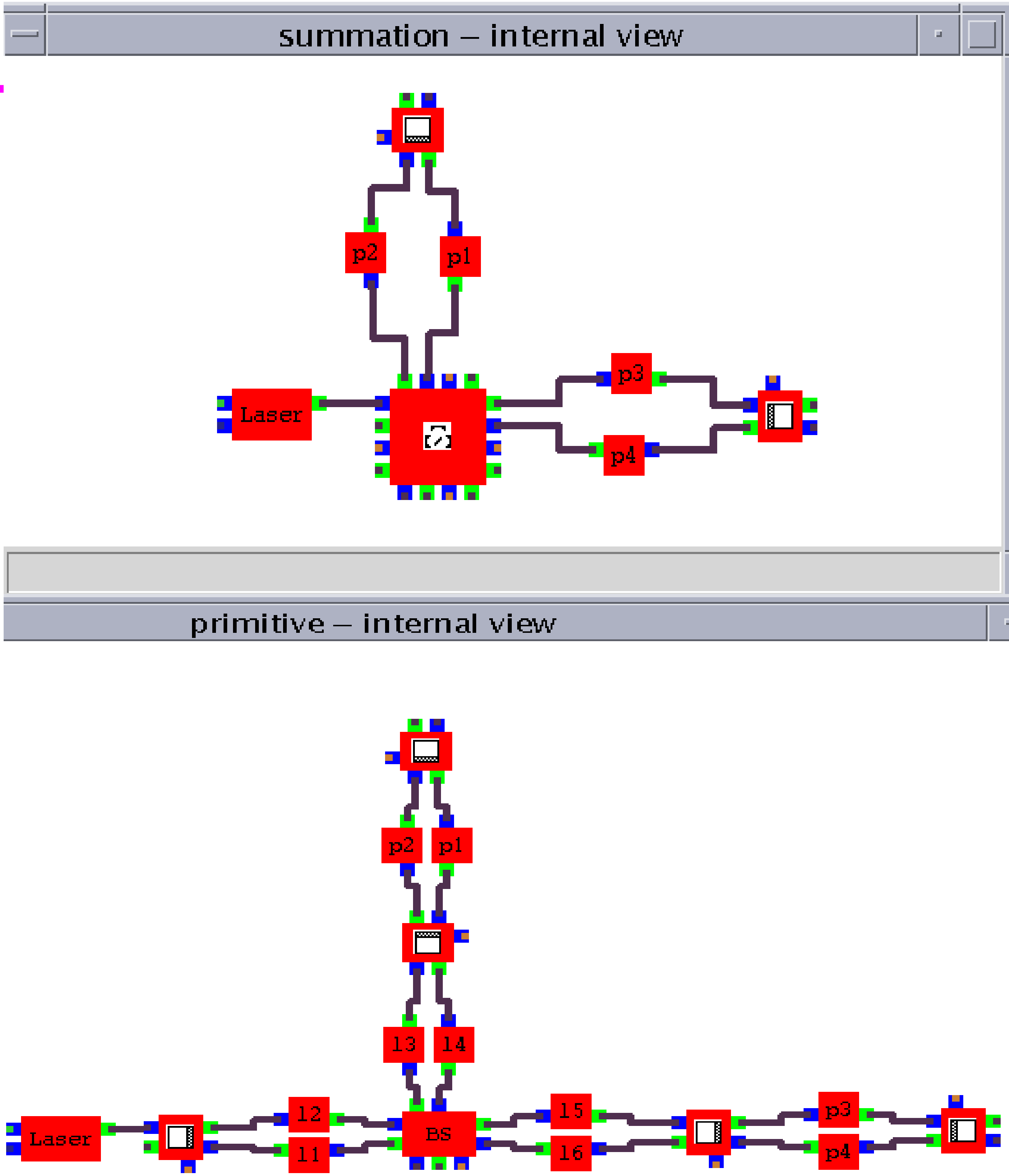
Using primitives: time-step = Length/speed of light



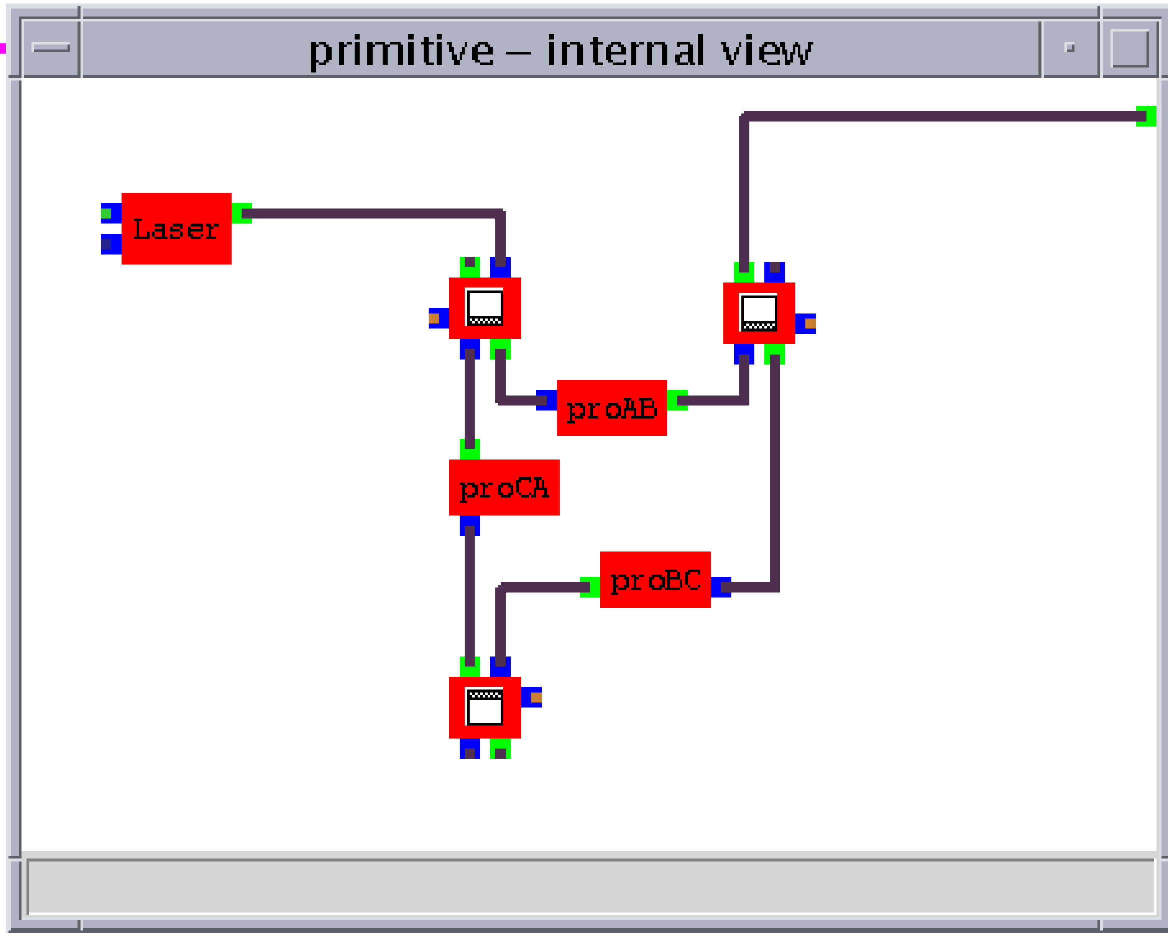
Using summation cavity:
time-step = N X Length/speed of light

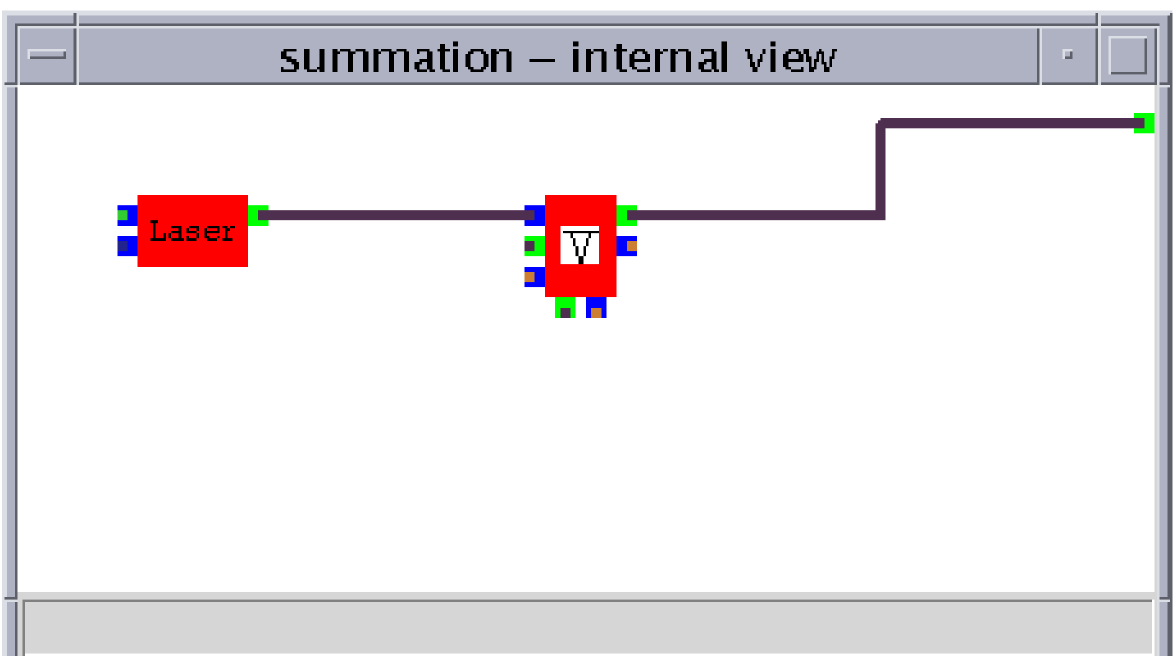
- Three modules so far
  - Fabry-Perot cav
  - triangular cavity
  - power-recycled Michelson cavity or the LIGO recycling cavity

Summation cavity in LIGO



Triangular cavity





Digitizer

- Analog data: discrete time-series of e2e with small time-steps
- Digitized data: sampled at larger time-steps (e.g. 16K circuit)

- Digital filter
  - characterised by poles, zeros, polepairs and zeropairs of equivalent analog filter
  - proper handling of data in discrete time-steps is done using z-transform internally
  - can be used as analog filter
  - to use in a digital circuit, it needs to be used in conjunction with ADC and DAC

ADC & DAC

- ADC

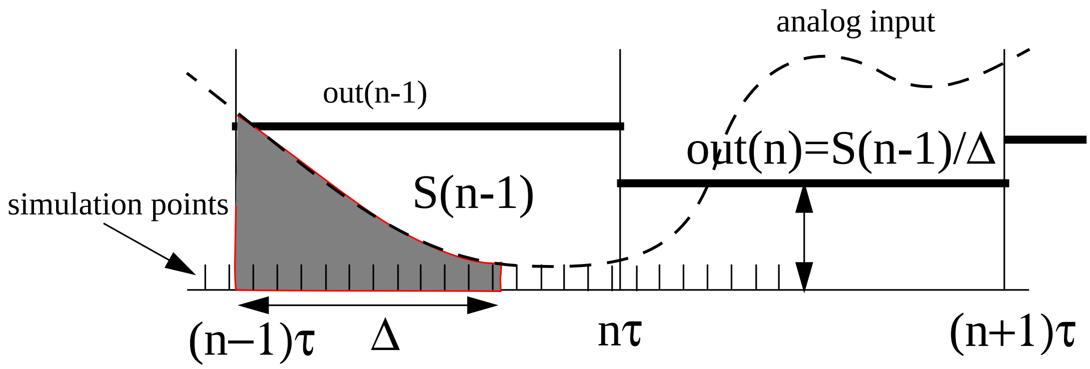


Figure 4: digitization in time

$$\mathrm{out}(n\tau) = \frac{1}{\Delta}\int_{(n-1)\tau}^{(n-1)\tau+\Delta} \mathrm{input}(t)dt$$

$$\mathrm{ADC}(n\tau) = \mathrm{floor}(\mathrm{gain}\cdot\mathrm{out}(n\tau) + 0.5)$$

   » output can be an integer in between limits specified by setting maximum no of bits

- DAC

Mechanics

- » susp3Dmass

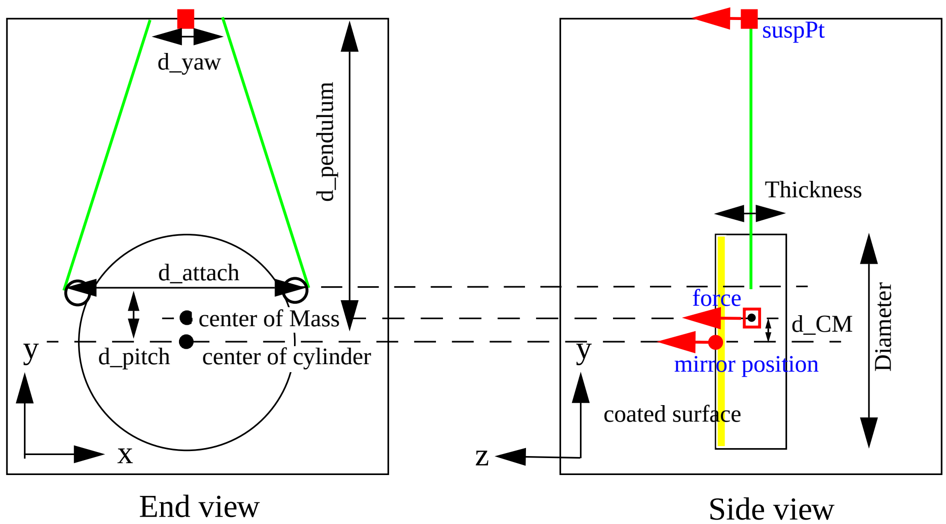


Figure 5: Single Suspended Mass

Coordinate system:

- AxisRotation

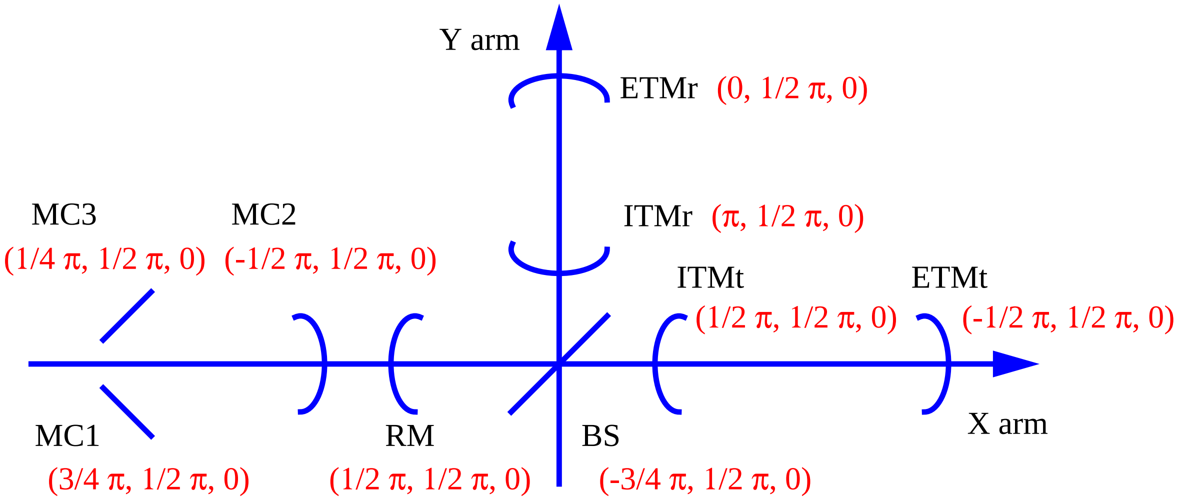


Figure 6: Detector to e2e coordinate transformation

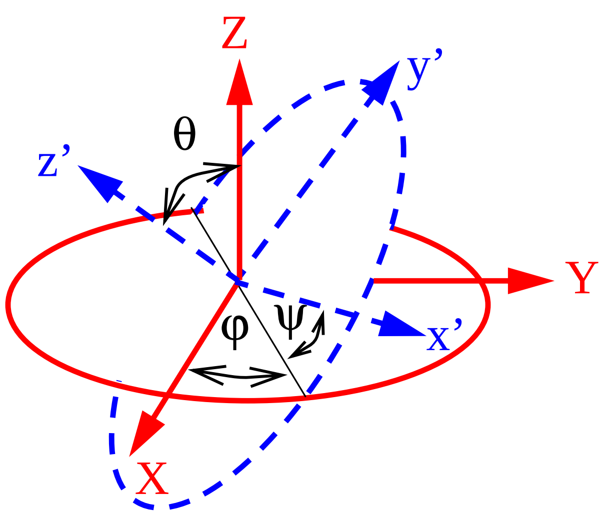


Figure 7: Euler angles

Math functions

- algebraic: madder (ax+by), sine, square_root, inverse ...
- logic : and,or,xor, a>b, not, flipflop, switch
- limiter, delay, switch

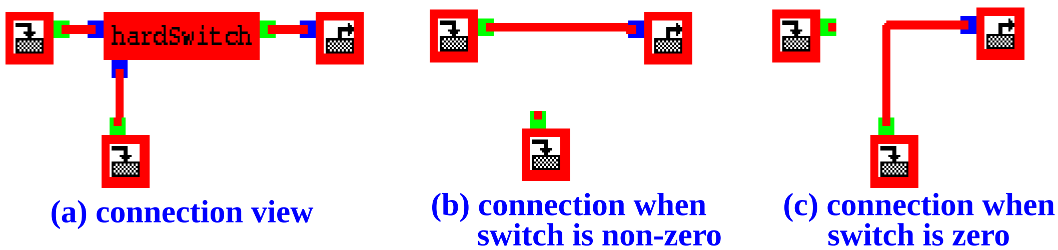


Figure 8: hardSwitch in action

- In many cases, better to use FUNC()

Data
input and output

- generating inputs
  - clock (time) : may also use get_time() function in Func()
  - random number (normal)
  - random number (flat)
  - data_in : can get a data into simulation
  - data_reader : can read input data from an ascii file

- Output
  - data_out : can get a data out of the simulation (‘probe’)
  - data_viewer: view data at a particular instant
  - psd_out: accumulate input data, calculate psd and write to a file