E2E: Physics Inside

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LIGO, Caltech

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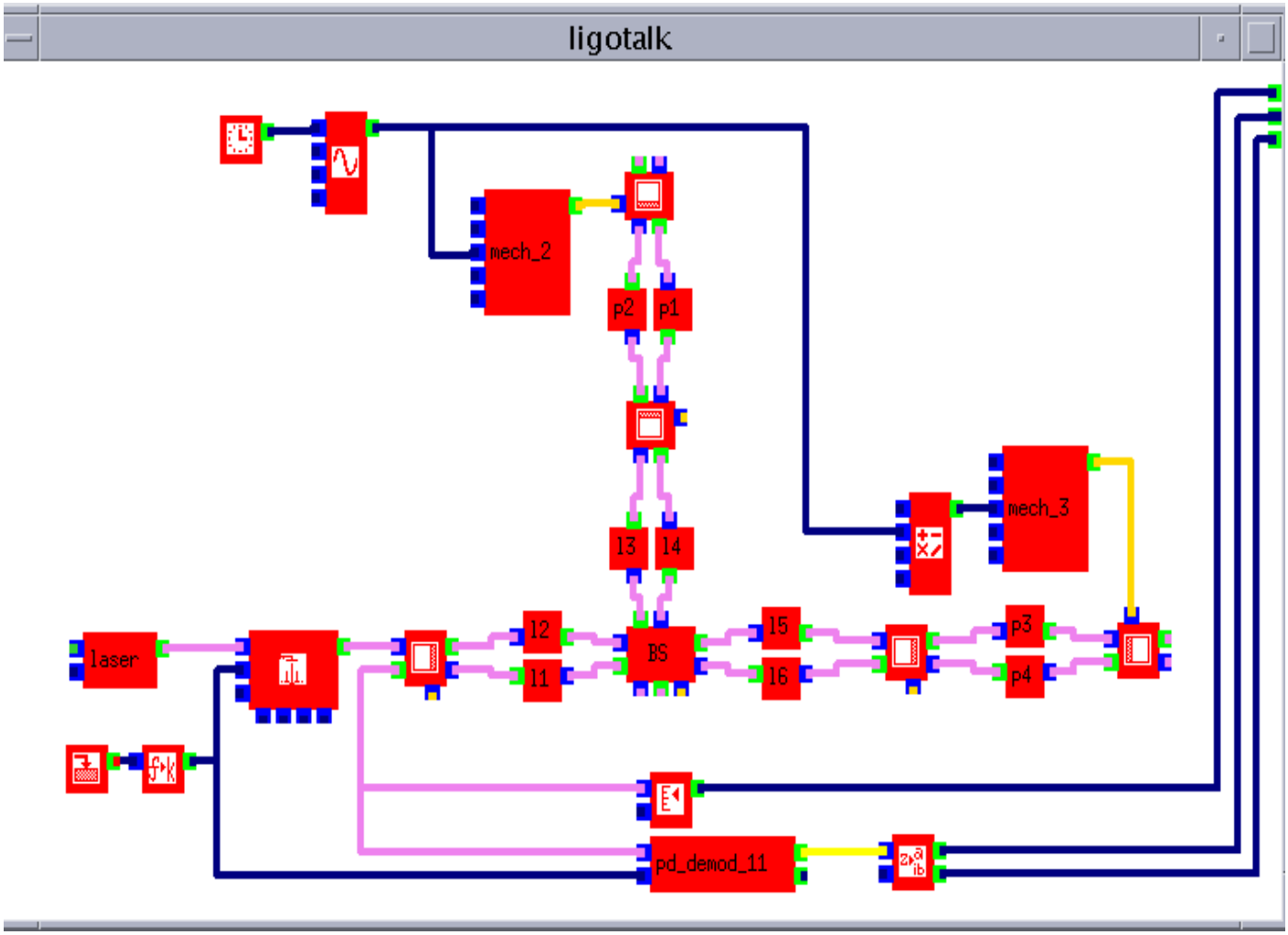
- October 18, 2000
- End-to-End meeting, Caltech

Example E2E box: LIGO L-
(using primitive modules)



- LIGO : a coupled, dynamic, multilength, nonlinear system

Build up your Laboratory

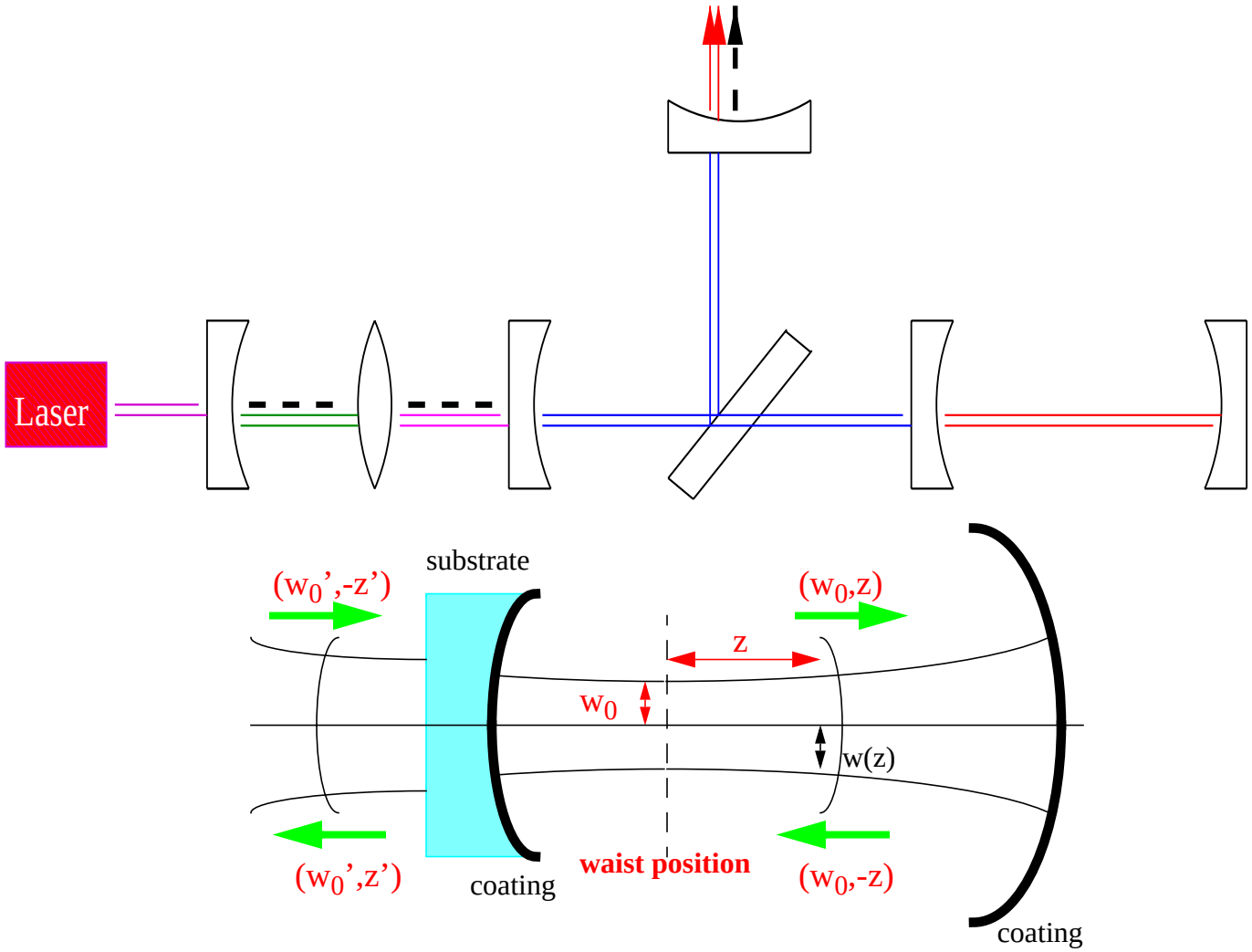
- Set-up your experiment using an easy-to-learn graphical-user-interface called Alfi

- Basic Tools (Primitive modules)
  - “field-gen” module (laser source), mirror, propagator, telescope, lens, modulator, detector, digital filter, power-meter, ...simple algebraic and logic functions..... etc.

- “field”
  - carries information about laser in the form of a vector of a vector
  - parent-vector: frequency child-vector: spatial modes
  - carries information about spatial modes in Hermite-Gaussian basis

- Set parameters of modules, make connections among them, ... run ....

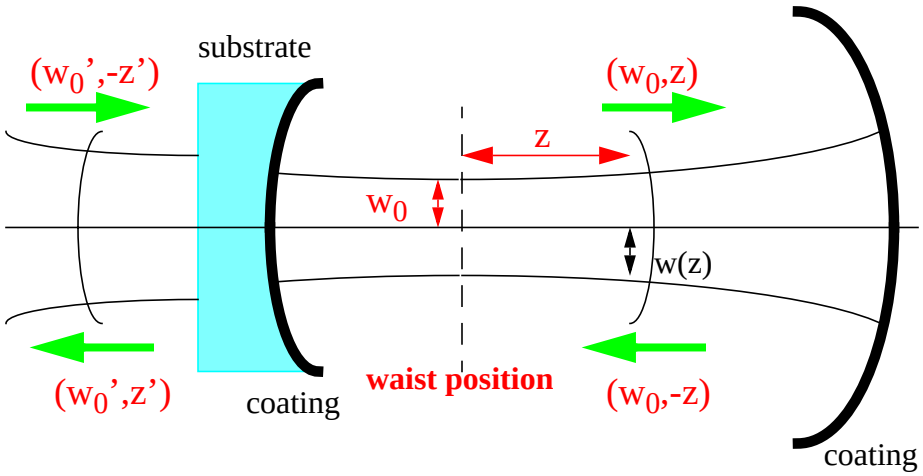
Time-domain modal model



- 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

Important settings
in laser (field_gen)

- max_mode_order: -1, 0, 1, 2, 3
- Calculate proper modal basis at the laser
  - using utility code modecal
- compute_mismatch_curvature: yes/no
- angle_resolution: depends



- Remember : length (in propagator) is always the resonant length for the carrier TEM00

- Question: what's the resonant length for the misaligned case?
- (long.+Gouy) Phase for TEM00= integer * half wave-length (?)

misalignment effects

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

$$A U_0$$

- Rotation (r) :

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

- lateral displacement (d) :

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

- Waist-position mismatch (b) :

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

- Waist-size mismatch (s) :

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

  - ›› We're trying to improve mismatch_curvature calculation e.g. introducing expansion of incoming beam at the input mirrors in the proper basis of the cavity

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)
  - Future: thermal lensing

Choice of time-step
(primitives)

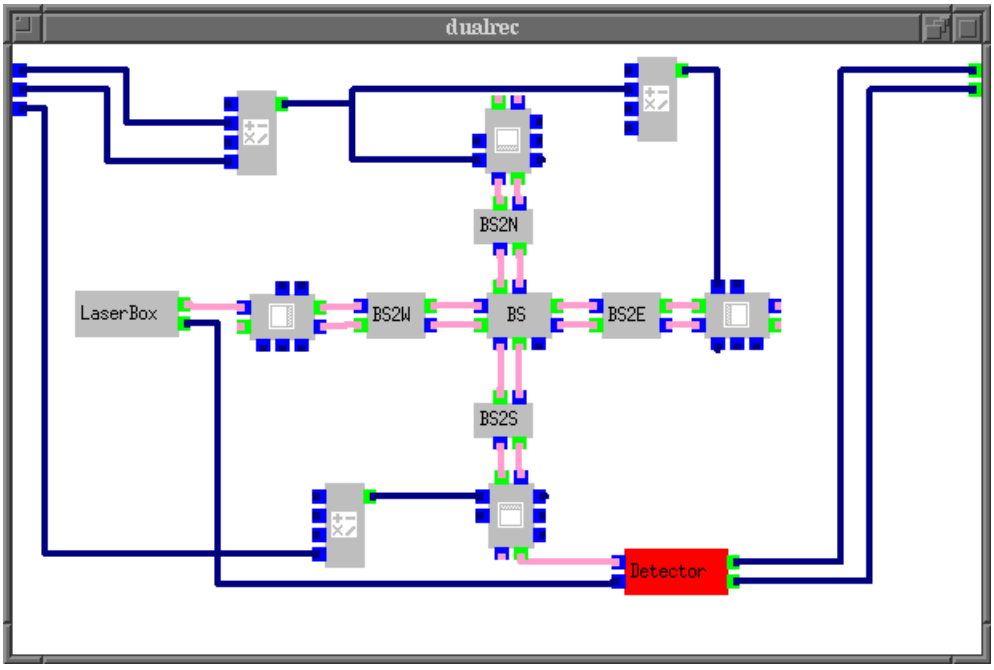
- Primitive run : time-step => at most that corresp. to the shortest propagator involved.

- In certain cases, setting *have-delay* (in propagator module) to **no**, is advantageous:

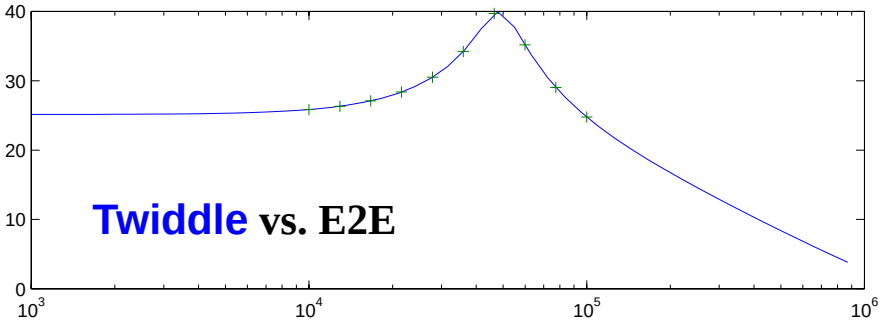
  - Power/Dual recycling with long delay-line arms: use time-step for arms instead of that for the length between beam-splitter and recycling mirror.

  - Triangular-cavity: set time-step to that of the long side

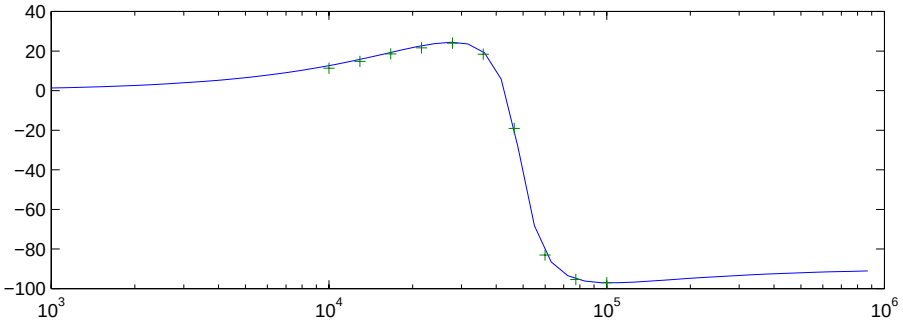
Dual-recycled IFO
(using primitive modules)



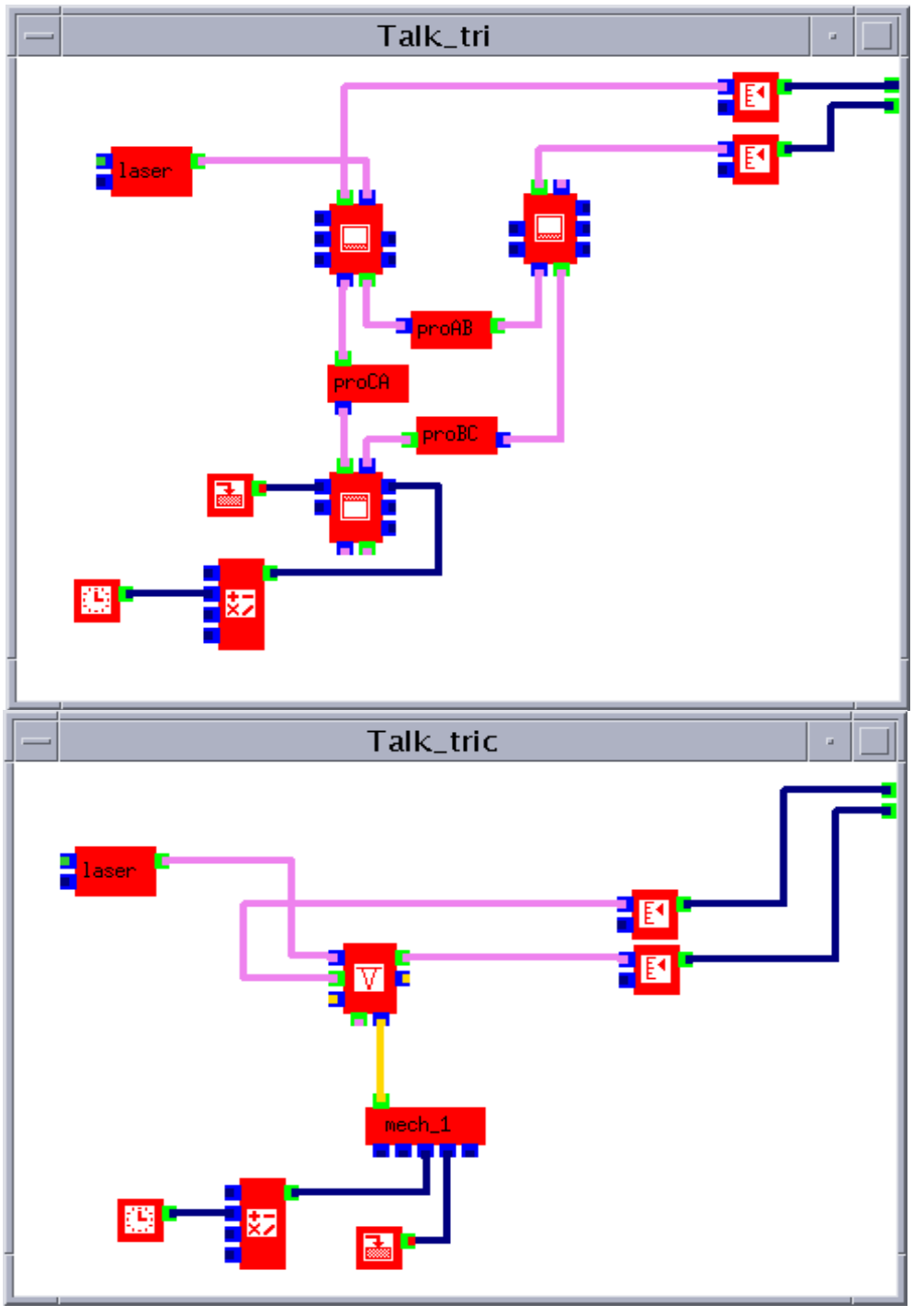
amplitude



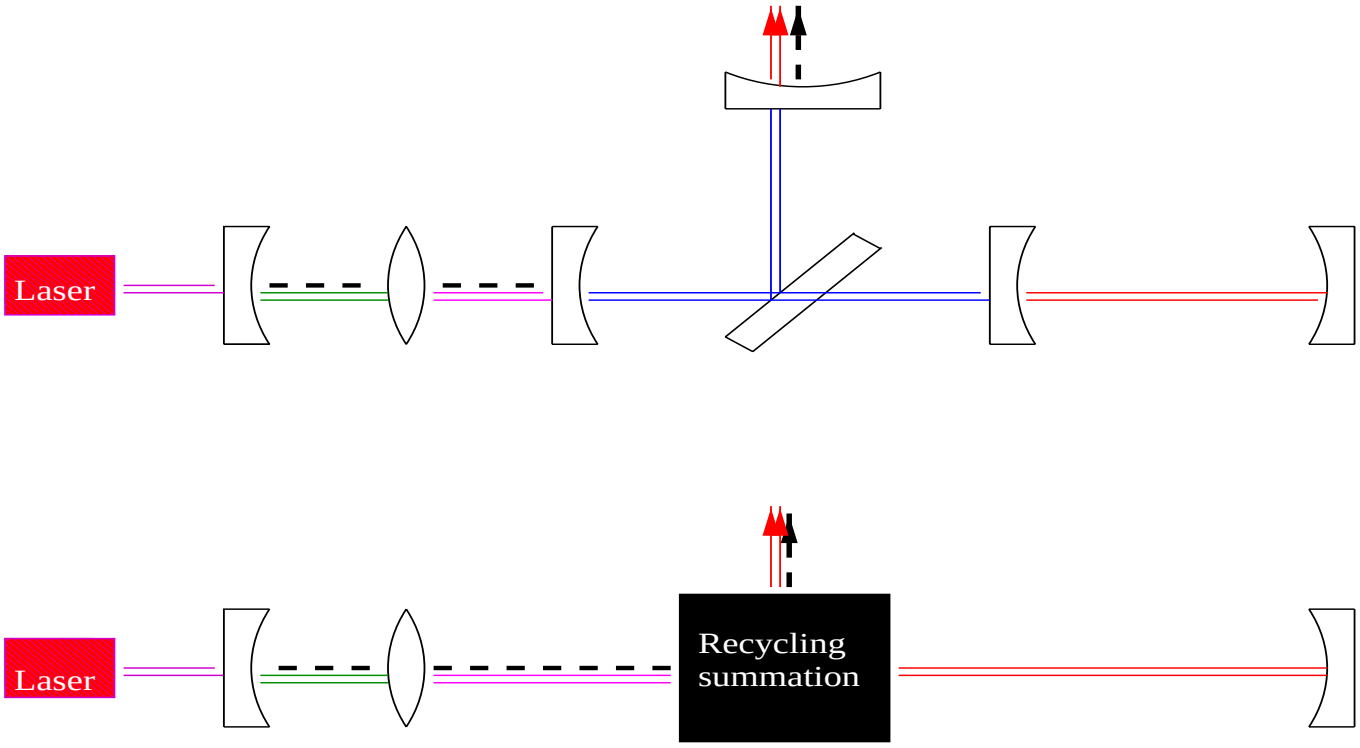
phase



Triangular cavity

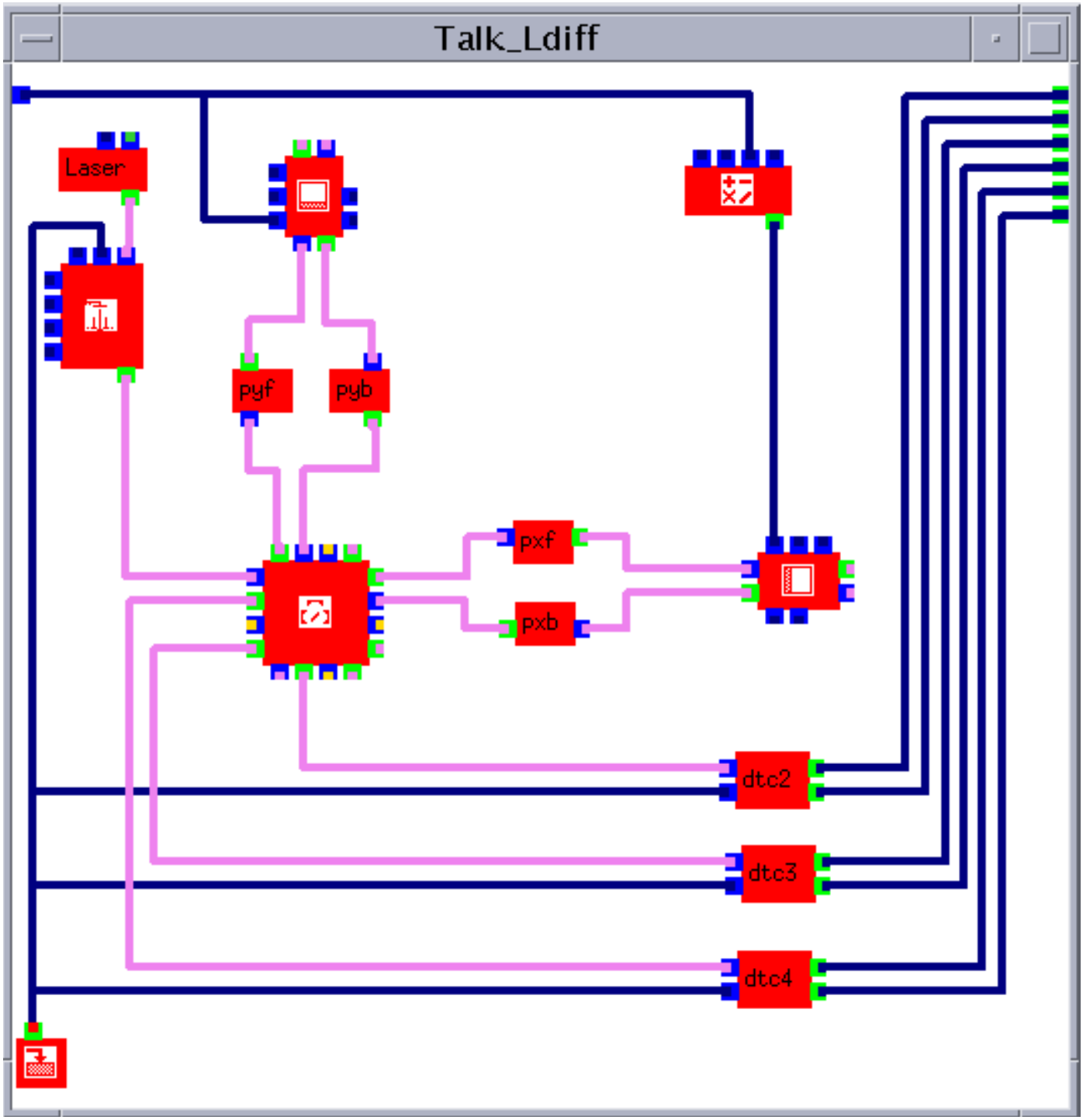


Composite Systems
(*summation modules*)



- Aim: fast computation
  - Fabry-Perot cav
  - triangular cavity
  - power-recycled Michelson cavity or the LIGO recycling cavity

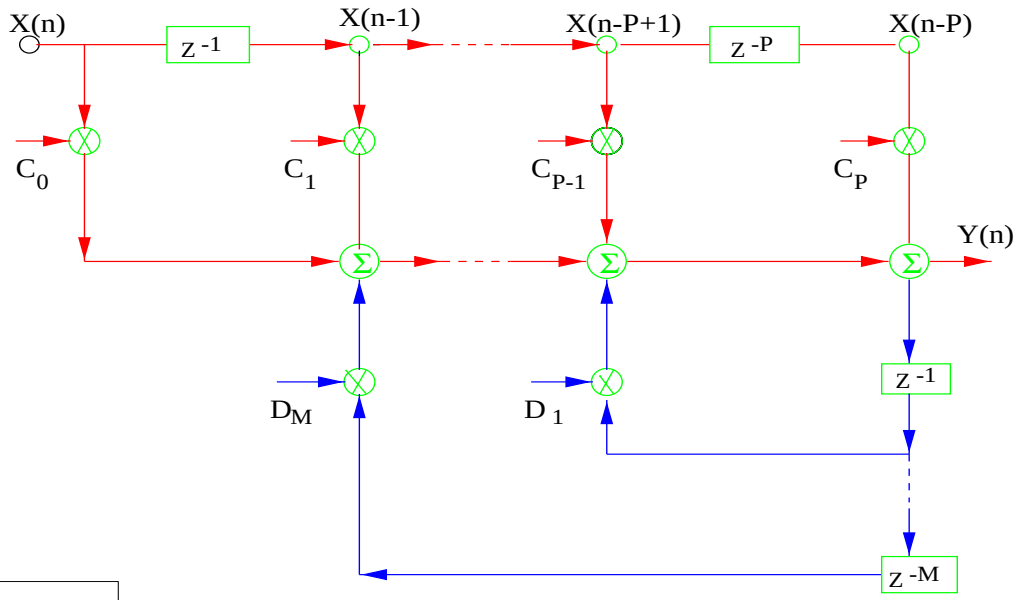
LIGO - L⁻ mode
(using recycled Michelson summation module)

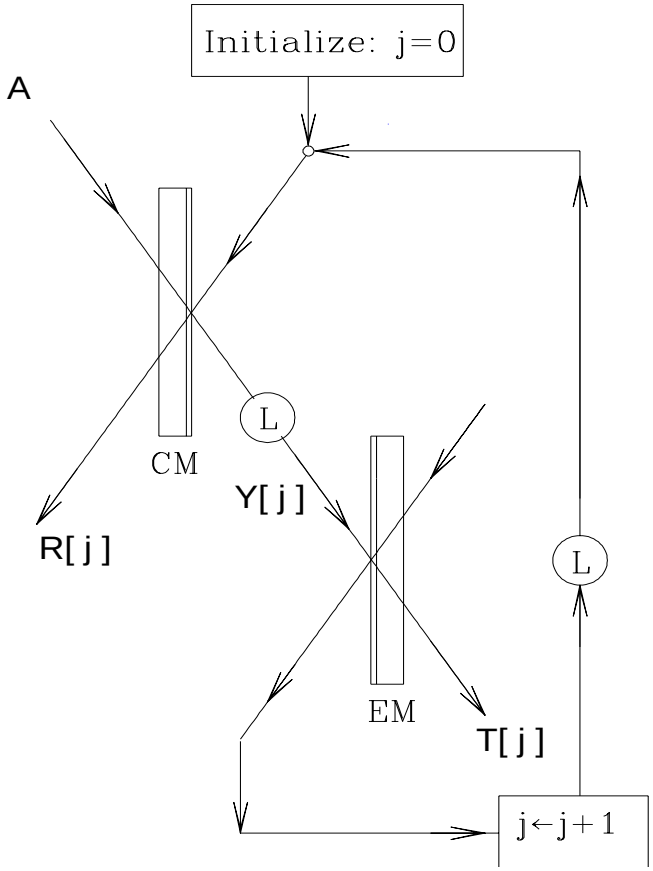


Time-step
(involving summation cavities)

- Summation cavity running alone:
  - shortest time-step allowed: one round-trip time of the cavity (caution: recycling_summation cavity)
  - Longest time-step: depends on various factors like storage-time of cavity and speed of mirrors
- Summation cavity + primitives (e.g. current LIGO run)
  - Time step = an integer or near-integer multiple of rtt of summation cavity
  - Time step < or = the smallest propagator involved in primitive part

Cavity as a digital filter



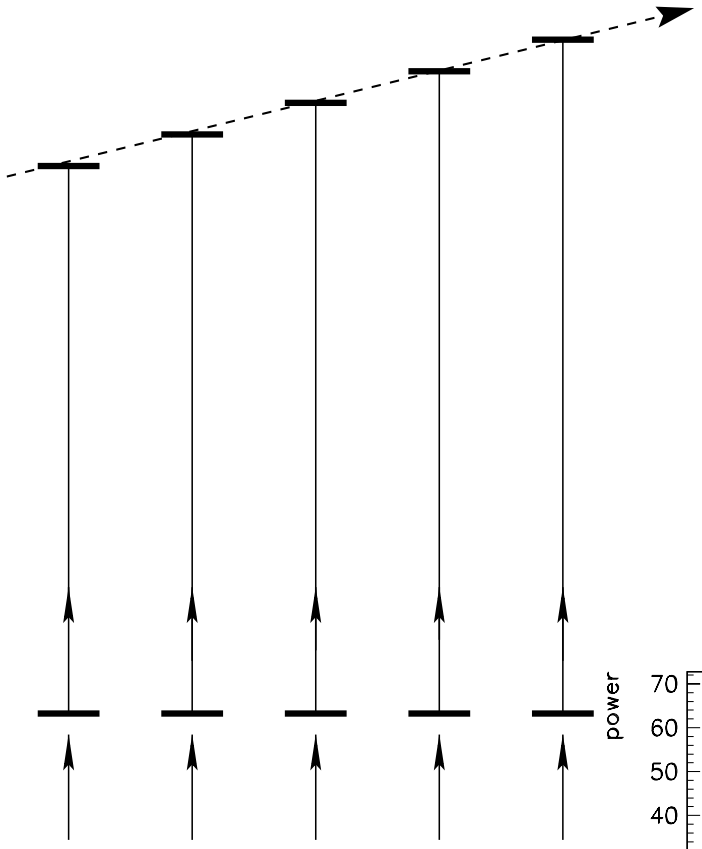


Whole diagram: An **IIR** filter
Red Part : A **FIR** filter

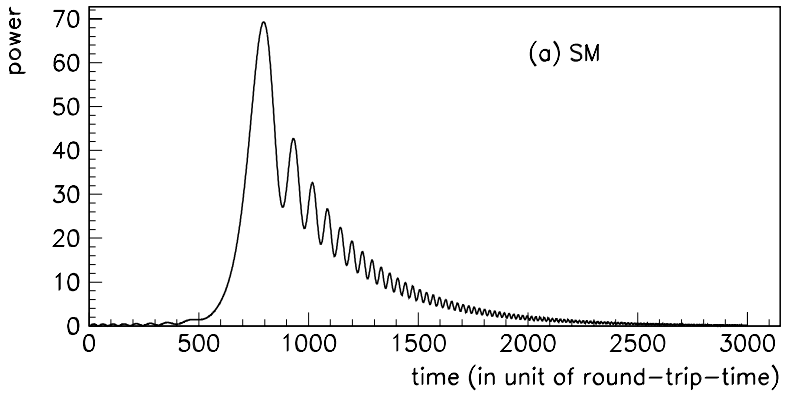
Cavity in general is an IIR filter
A low finesse cavity is a FIR filter

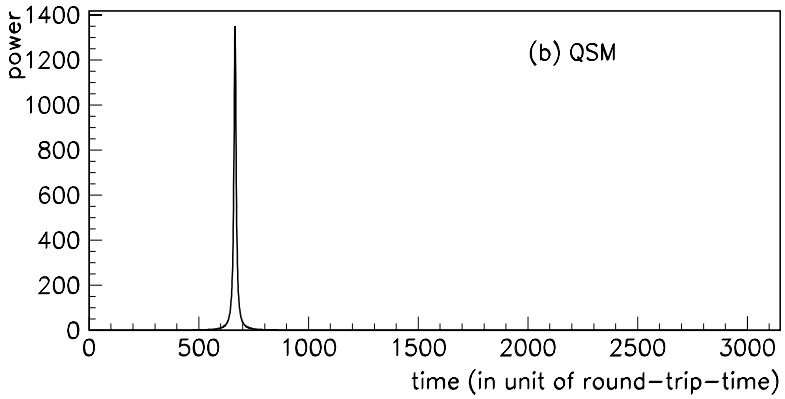
Summation cavity calculations performed using linear approx in short time-steps
(= several round-trip-time)

FP cavity: length changing
(compare static & dynamic)

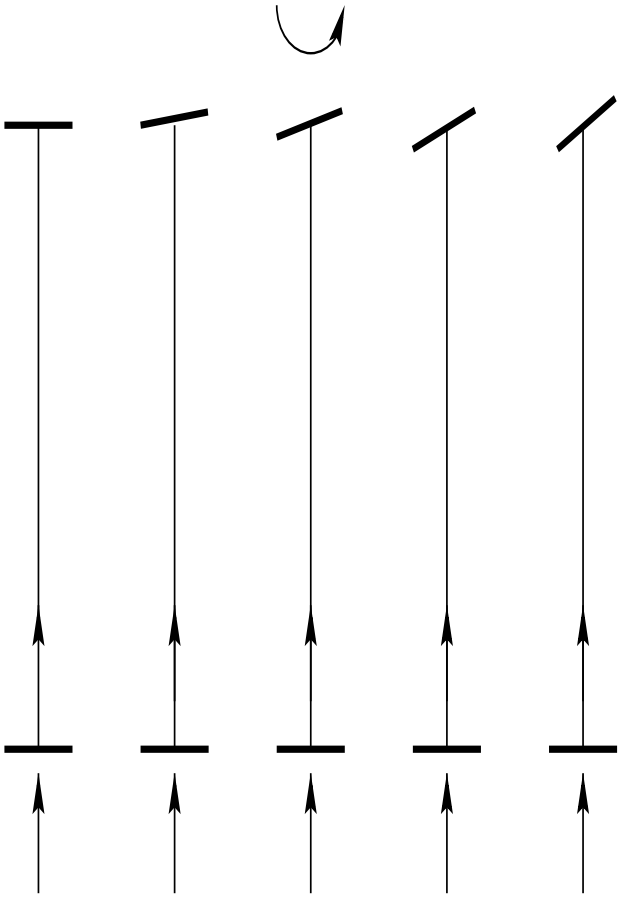


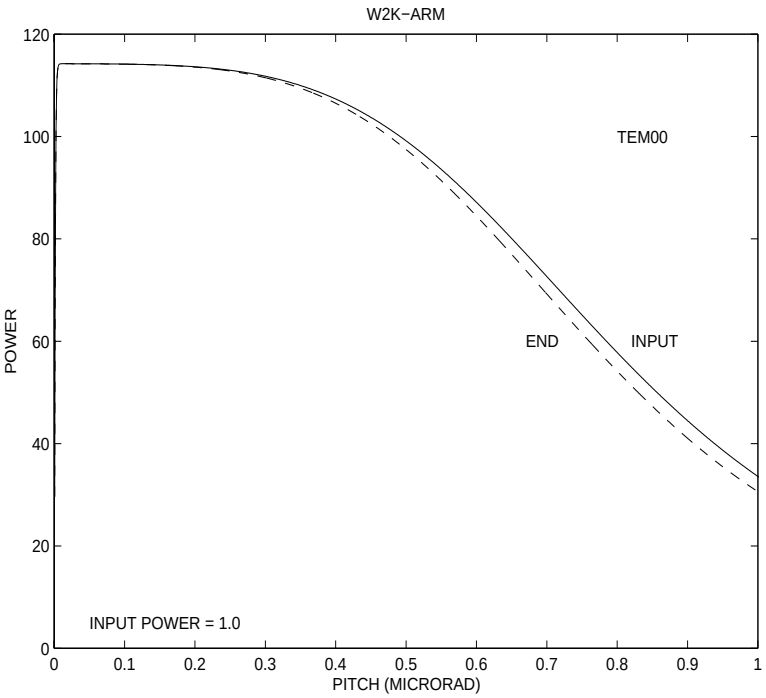
Speed & finesse (storage time) important parameters in summation cavity calculations

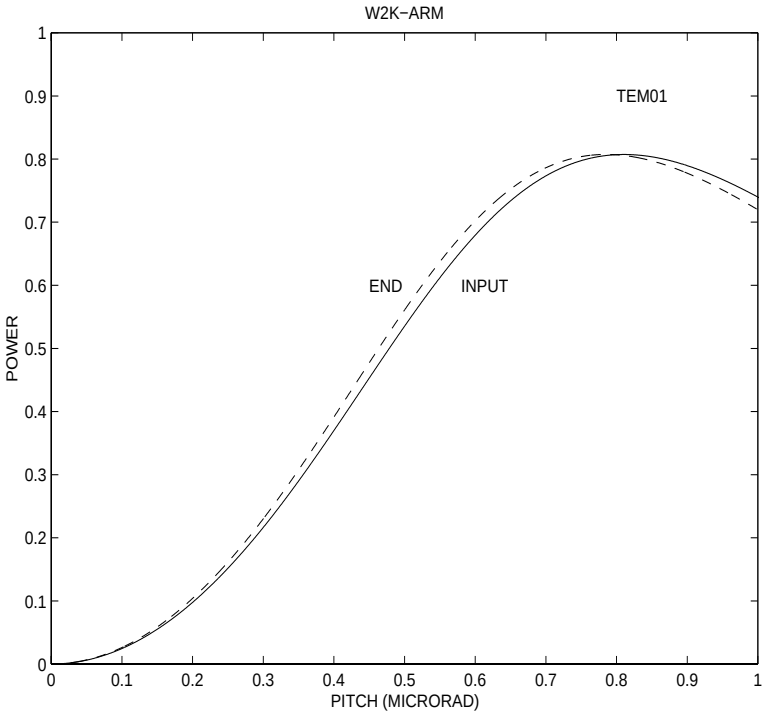




FP cavity: pitch/yaw changing
(compare static and dynamic)





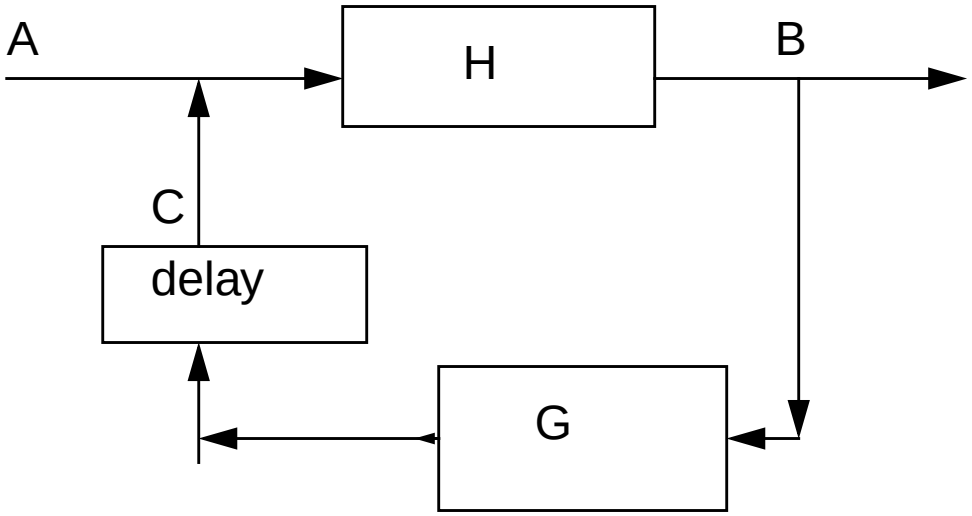


rate of change in misalign -ment not important for summation cavity calculation

Time-step
(& Summation cavities)

- Upper limit on time-step depends on storage-time cavity & speed of mirrors.
- Reference cavity, Mode-cleaner, Pre-mode-cleaner : A step of ~ thousand rtt or more may be allowed in isolated run.
- Recycling summation cavity: Lo Finesse system : several hundred rtt may be allowed
- Full LIGO Cavity (not implemented yet) :
  Hi Finesse system : several 10s depending on speed involved
-
- Problem : When used in closed control loop that involves high frequencies.

Closed loop problem



B(t) = H * (A(t)+C(t))
C(t) = G * B(t)
Approx. => C(t) = G * B(t - ‘time-step’)

B ~ b exp(i w (t- ‘time-step’))

Bad Approx. : if freq w is high

* Problem in PSL
  (zeros and poles at 10K level)
* Not a problem in core-optics
  (zeros and poles at 10-100 level)

tasks ahead

- introduction of thermal lensing effect
- more accurate implementation of mismatch-curvature calculation
- new field implementation
- summation cavities for full LIGO-I & II and recycling cavity of LIGO II
- speeding up the code especially in misaligned and closed loop cases
- .....