Interferometer Design Considerations

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LIGO-G950037

INTERFEROMETER DESIGN CONSIDERATIONS

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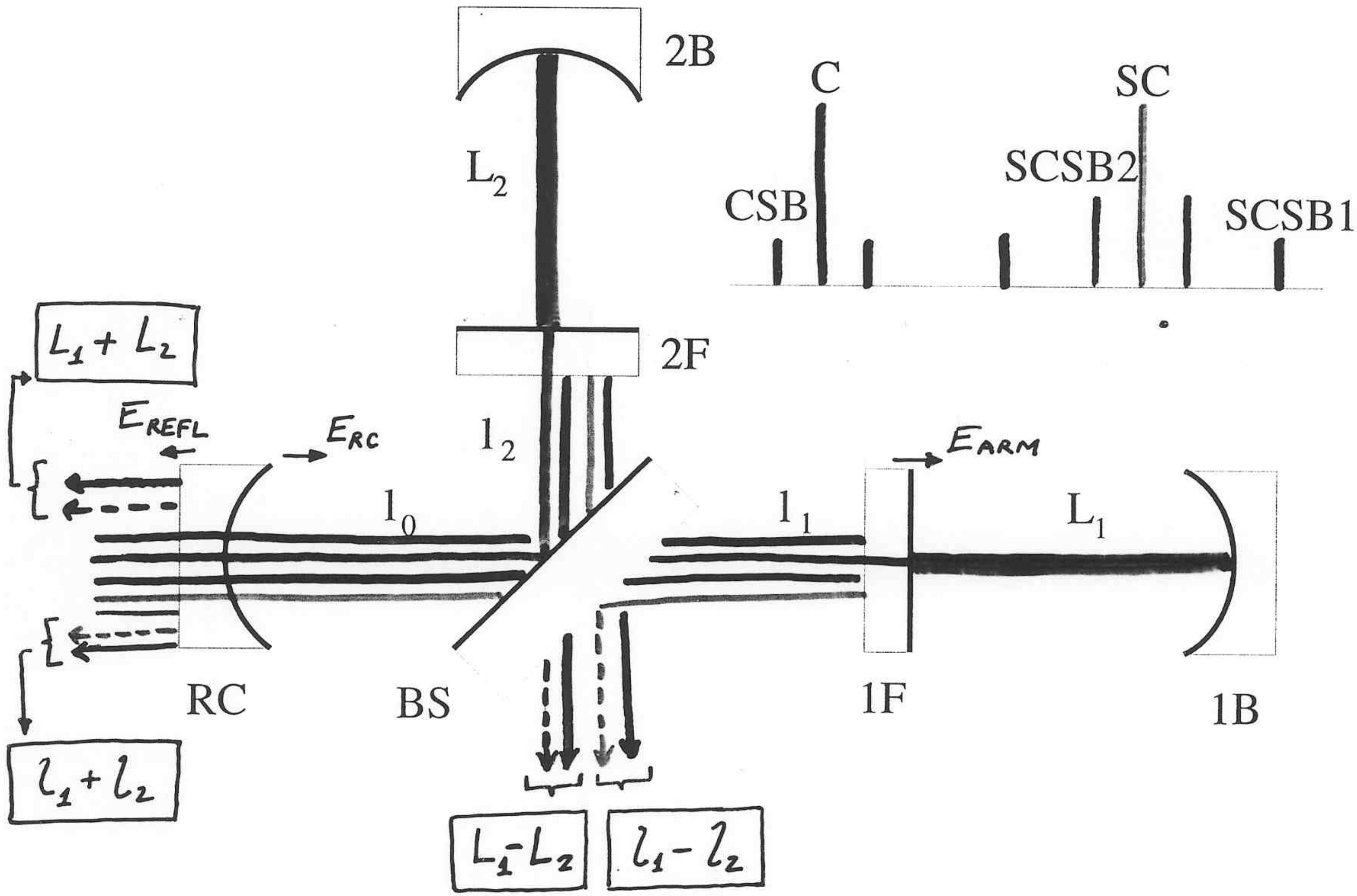
DESIGN CONSIDERATIONS FOR THE FMI II

- Introduction/motivation
- Description of the interferometer configuration
- Selection criteria for relevant parameters
- Proposed FMI design
- Implications for a long baseline interferometer

MOTIVATION

- FMI
  - Table top experiment
  - Testbed for a probable LIGO length control scheme
  - Testbed for wavefront sensing technique for alignment control
- Robust longitudinal lock is a prerequisite for the alignment measurement
- Design FMI carefully to diagonalize length sensing matrix
- Same algorithm can be applied to optimize parameters of a long baseline interferometer but subject to different constraints

DESCRIPTION OF INTERFEROMETER CONFIGURATION



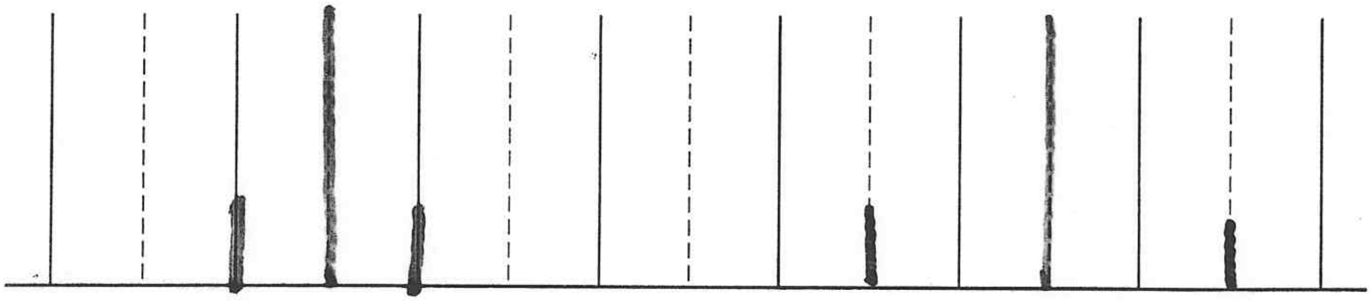
INTERFERING FIELDS	SIGNAL SENSED AT	DEGREE OF FREEDOM	
C and CSB	anti-symmetric port	L_1-L_2	differential arm cavity length
C and CSB	reflected from recycling mirror	L_1+L_2	common mode arm cavity length
FSSC and SCSB1	anti-symmetric port	l_1-l_2	differential Michelson length
FSSC and SCSB2	reflected from recycling mirror	l_1+l_2	common mode Michelson length

SELECTION CRITERIA

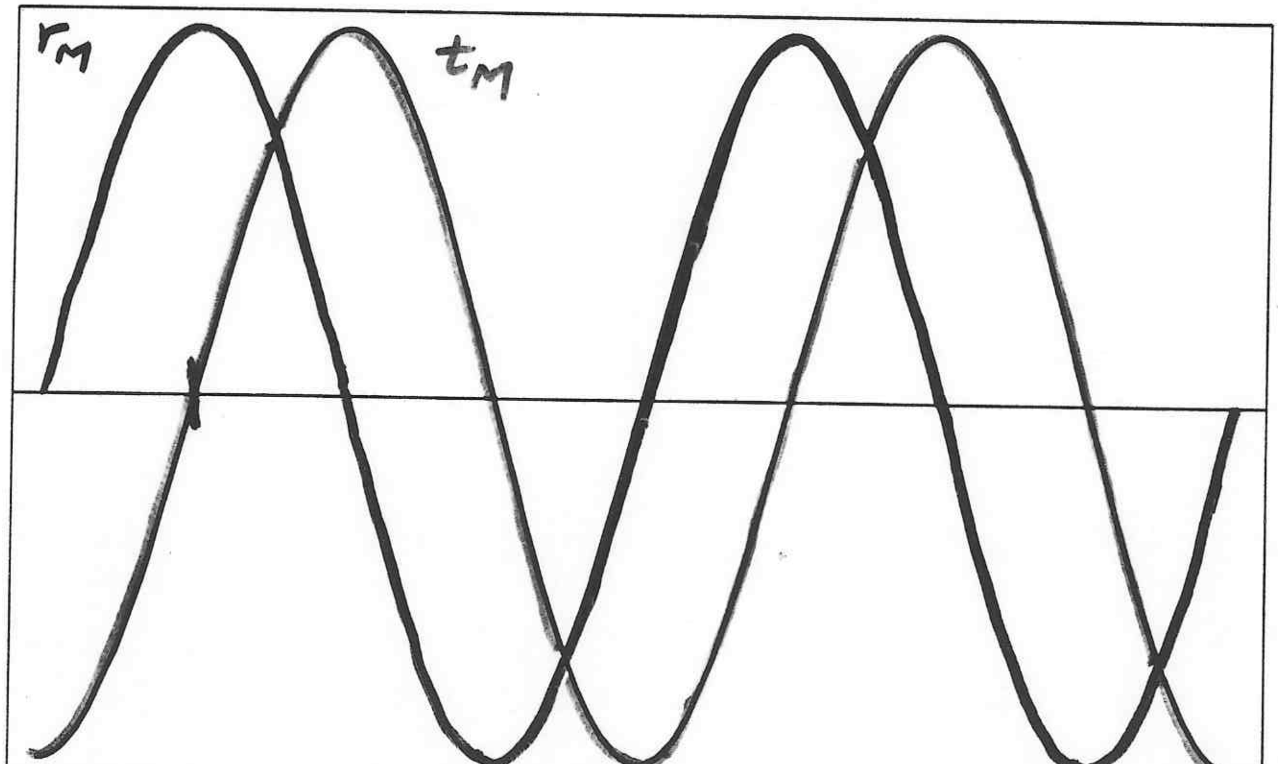
MODULATION FREQUENCIES

FREQUENCY	PHYSICAL OR TECHNICAL CONSTRAINTS	SELECTION CRITERIA
Carrier at $\Delta\nu = 0$.	None.	(i) Must resonate in both recycling and arm cavities, and (ii) minimum carrier light must exit the antisymmetric port.
Half free spectral range of recycling cavity, f_0.	Should not exceed 20 MHz, since carrier sideband could be at $\Delta\nu = 3\,f_0$, and we avoid modulating the Pockels cells at frequencies greater that 60 MHz.	Depends only on the length of the recycling cavity.
Frequency shifted subcarrier at $\Delta\nu_{FSSC} = n\,f_0$.	Constrained by center frequency of commercially available acoustooptic modulators.	(i) Must resonate in recycling cavity, i.e. $\Delta\nu = n\,f_0$, where $n > fsr_{ARM}/fsr_{RC}$ and n even, (ii) must be anti-resonant in arm cavity, and (iii) minimum subcarrier light must exit the antisymmetric port.

FREQUENCY	PHYSICAL OR TECHNICAL CONSTRAINTS	SELECTION CRITERIA
Carrier sideband at $\Delta\nu_{CSB} = f_0$ or 3 f_0.	(i) Modulate at frequencies greater than 5MHz, else laser is not shot noise limited, (ii) avoid exceeding 60 MHz, and (ii) avoid using $\Delta\nu = f_0$, since J_2 term coincides with subcarrier sideband at $\Delta\nu = 2 f_0$.	Must resonate in recycling cavity while experiencing π phase shift relative to the carrier due to arm cavity resonance, i.e. $\Delta\nu = f_0$, 3 f_0, 5 f_0,...
Subcarrier sideband at $\Delta\nu_{SCSB1} = 2 f_0$	Avoid frequencies less than 5MHz and greater than 60 MHz.	Must resonate in recycling cavity, i.e. $\Delta\nu = 2 f_0$, 4 f_0,...
Subcarrier sideband at $\Delta\nu_{SCSB2}$	Avoid frequencies less than 5MHz and greater than 60 MHz.	Avoid overlap with longitudinal and lower order transverse modes of recycling cavity to minimize coupling into interferometer.



$$r_M \propto \cos\left(\frac{2\pi f}{c} a\right) \qquad t_M \propto \sin\left(\frac{2\pi f}{c} a\right)$$

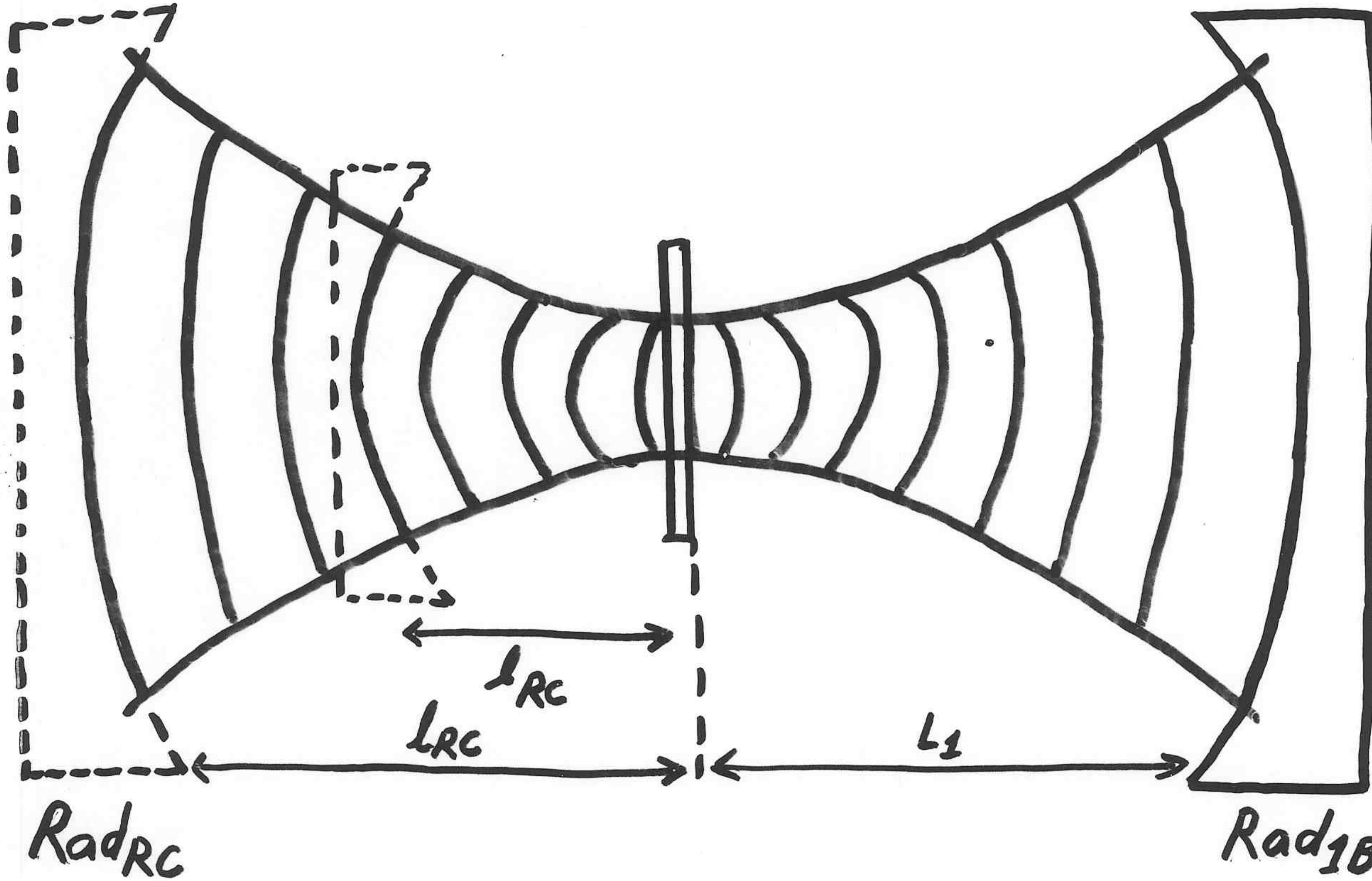


INTERFEROMETER LENGTHS

LENGTH	PHYSICAL OR TECHNICAL CONSTRAINT	SELECTION CRITERIA
Recycling cavity length, l_{RC}.	Cannot exceed 6.0 m or a third fold will be necessary.	Determined along with arm cavity length, L_1, by the mirror radii of curvature and the constraints on f_0.
Arm cavity length, L_1.	Cannot be shorter than 15 cm, nor longer than 1 m due to spatial considerations.	Determined simultaneouly with l_{RC}, once mirror radii of curvature are chosen.
Asymmetry	Tolerance to mismatch to be calculated.	Chosen so that the antisymmetric port is maximally dark for the subcarrier.

MIRROR RADII OF CURVATURE

MIRROR RADIUS OF CURVATURE	PHYSICAL OR TECHNICAL CONSTRAINT	SELECTION CRITERIA
Arm cavity rear mirror, Rad_{1B}.	Super polished mirrors subject to availability from LIGO inventory.	(i) Affects transverse mode spacing, i.e. chosen so transverse modes do not coincide with longitudinal resonances of cavity, and (ii) must be greater than length of cavity to satisfy stable resonator condition.
Arm cavity front mirror, Rad_{1F}.	Also super polished mirror (see above).	Chosen to be flat, but could, in principle, be a curved mirror to act as a lens for mode matching to compensate mismatch due to asymmetry.
Recycling mirror, Rad_{RC}.	Commercial (CVI) mirror, so we try to use stock curvatures, typically available in integral increments of 1 m.	(i) Simultaneously match the fundamental mode of the arm cavity and keep $l_{RC} < 6.0$ m, (ii) satisfy stable resonator condition, (iii) avoid overlap of transverse modes with longitudinal and transverse modes of both cavities, and (iv) avoid $\omega_{RC} > 1.5$ mm.

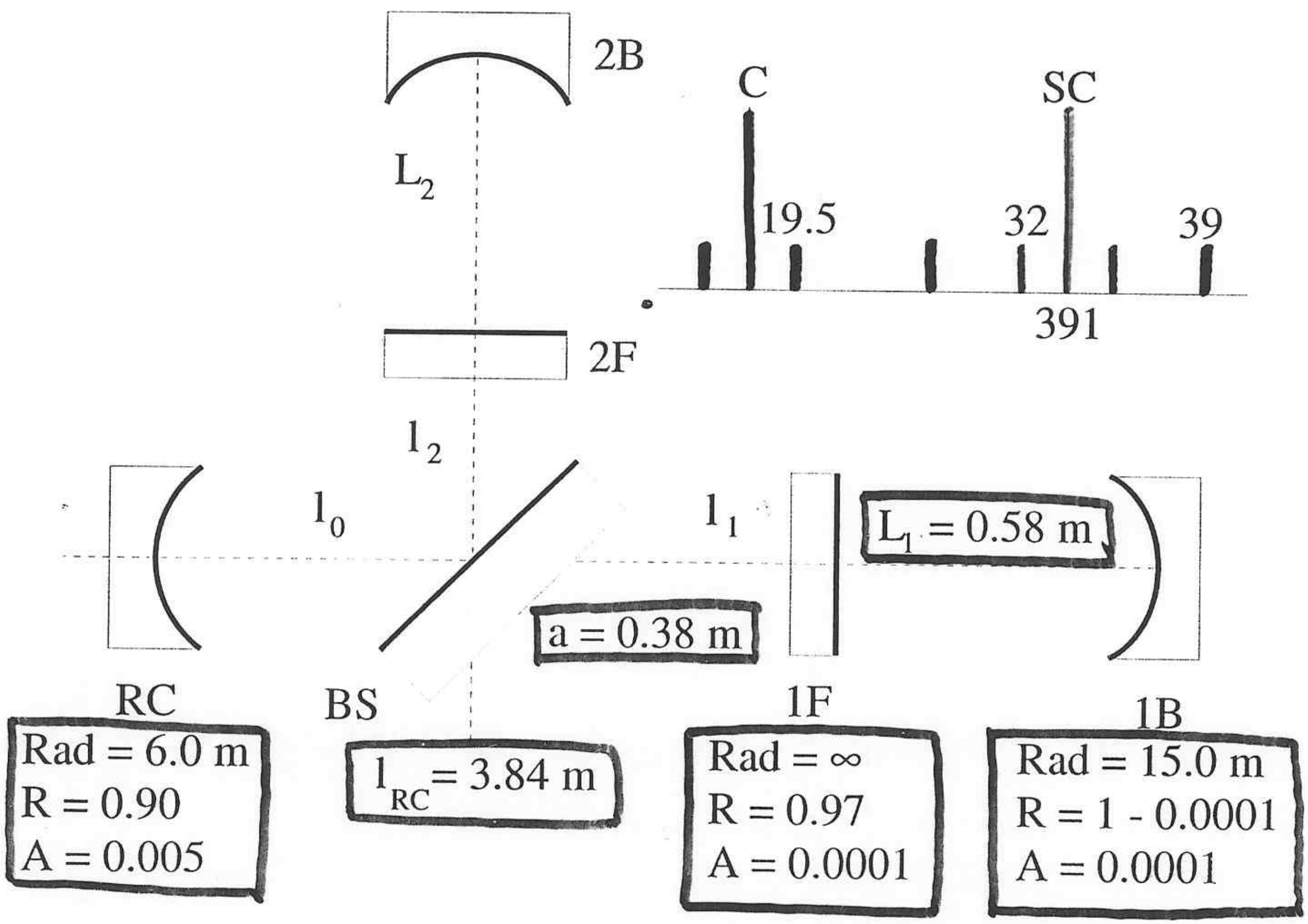


l_{RC}
l_{RC}
L_1
Rad_{RC}
Rad_{1B}

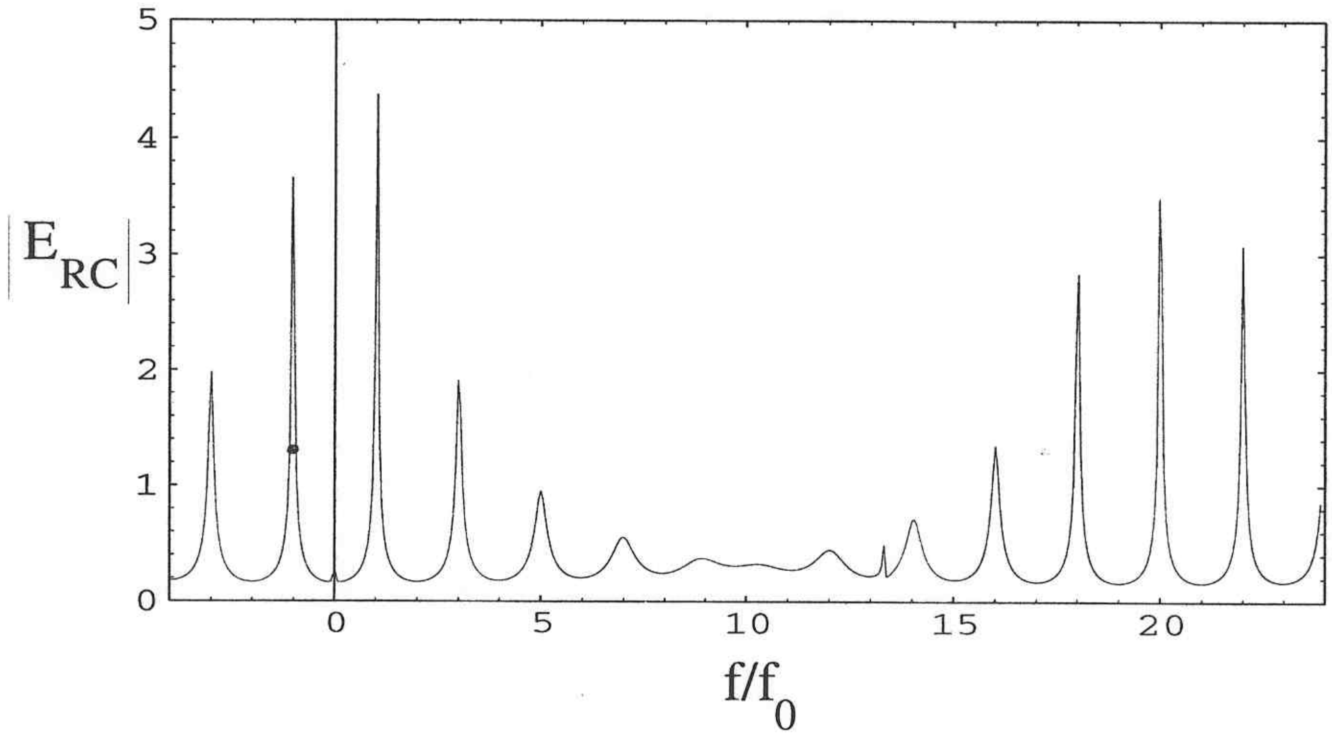
MIRROR REFLECTIVITIES

MIRROR REFLECTIVITY	PHYSICAL OR TECHNICAL CONSTRAINT	SELECTION CRITERIA
Arm cavity rear mirror, R_{1B}.	Super polished mirror specially coated at REO, subject to availability from LIGO standard inventory.	High reflection, T=10^{-4}, low loss, A=10^{-4}, mirror.
Arm cavity front mirror, R_{1F}.	Same as above.	Choose T=0.028 and A=10^{-4} to give 3% reflection loss from the arm cavity on resonance.
Recycling mirror, R_{RC}.	Commercial (CVI) mirror, available in stock reflectivities of integral increments of 5%.	In principle, critically couple the carrier, i.e. transmission of recycling mirror is equal to reflection losses from arm cavity on resonance. Actually choose a commercial reflectivity such that $T_{RC}>T_{crit}$. Strongly influences the diagonality of the length sensing matrix if SCSB2 is eliminated from the modulation scheme.
Beamsplitter, R_{BS}.	Commercial (CVI) element.	Specify as close to 50-50 as possible, so that (i) less sensitive to polarization changes, and (ii) lower the contrast defect.

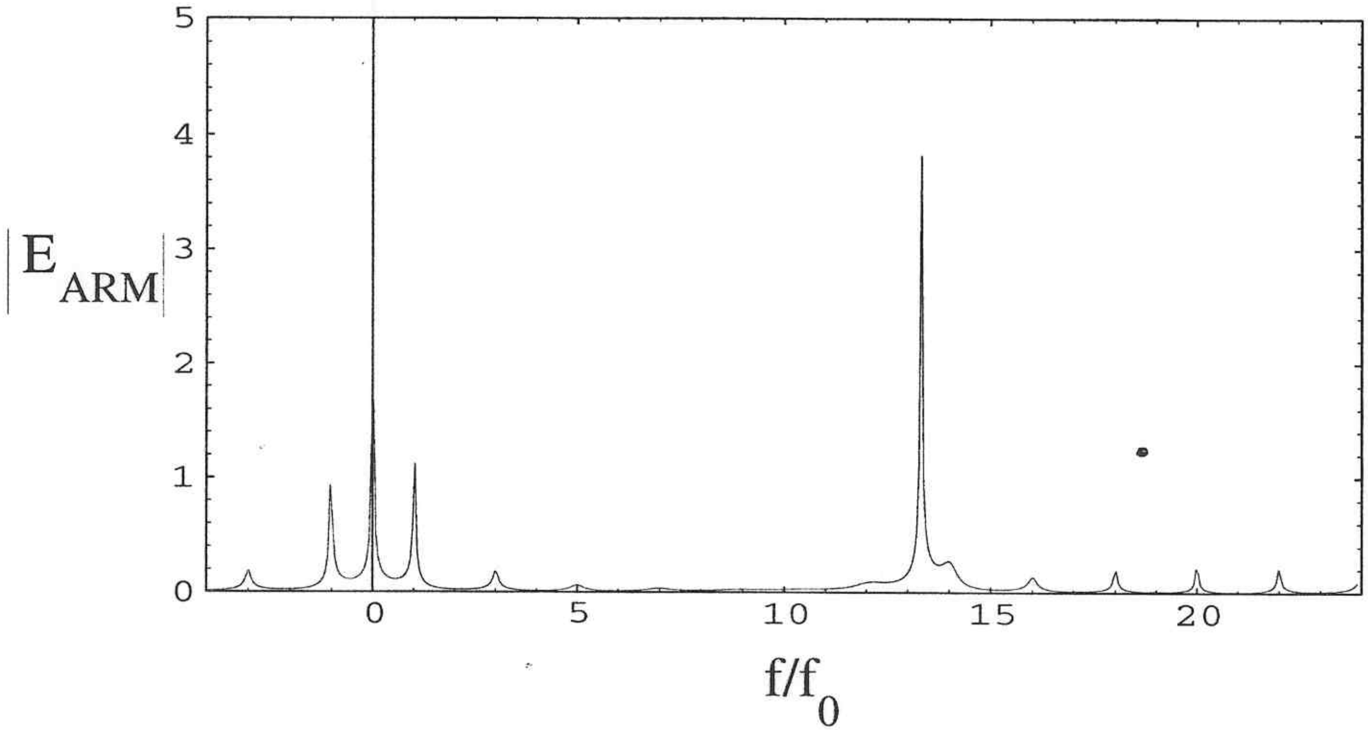
PROPOSED FMI DESIGN



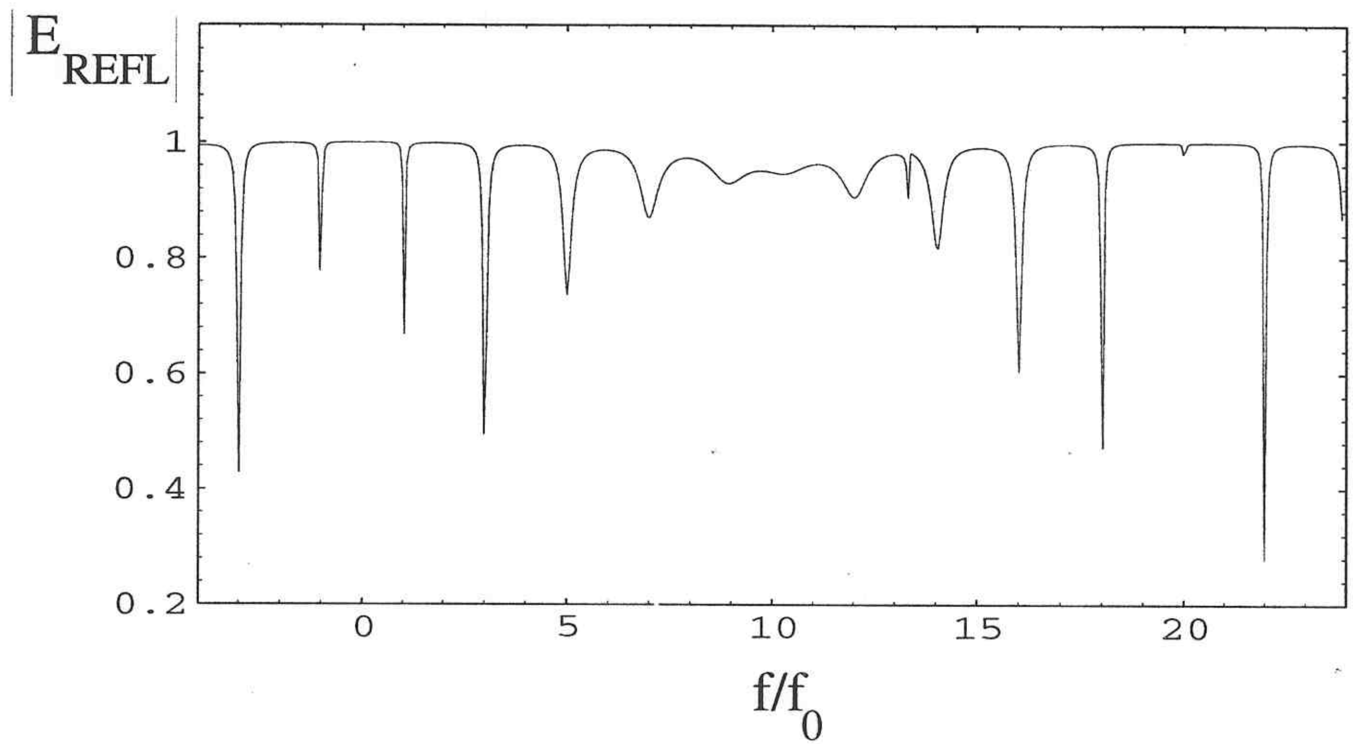
DETECTOR	GAIN	L_1-L_2	L_1+L_2	l_1-l_2	l_1+l_2
CSB antisymm	112	1.000	0.000	$7.6\ 10^{-3}$	10^{-17}
CSB refl	34	$7.1\ 10^{-3}$	1.000	10^{-16}	$2.6\ 10^{-5}$
SCSB1 antisymm	11623	$7.6\ 10^{-3}$	10^{-11}	1.000	10^{-11}
SCSB2 refl	1921	10^{-6}	$7.6\ 10^{-3}$	10^{-6}	1.000

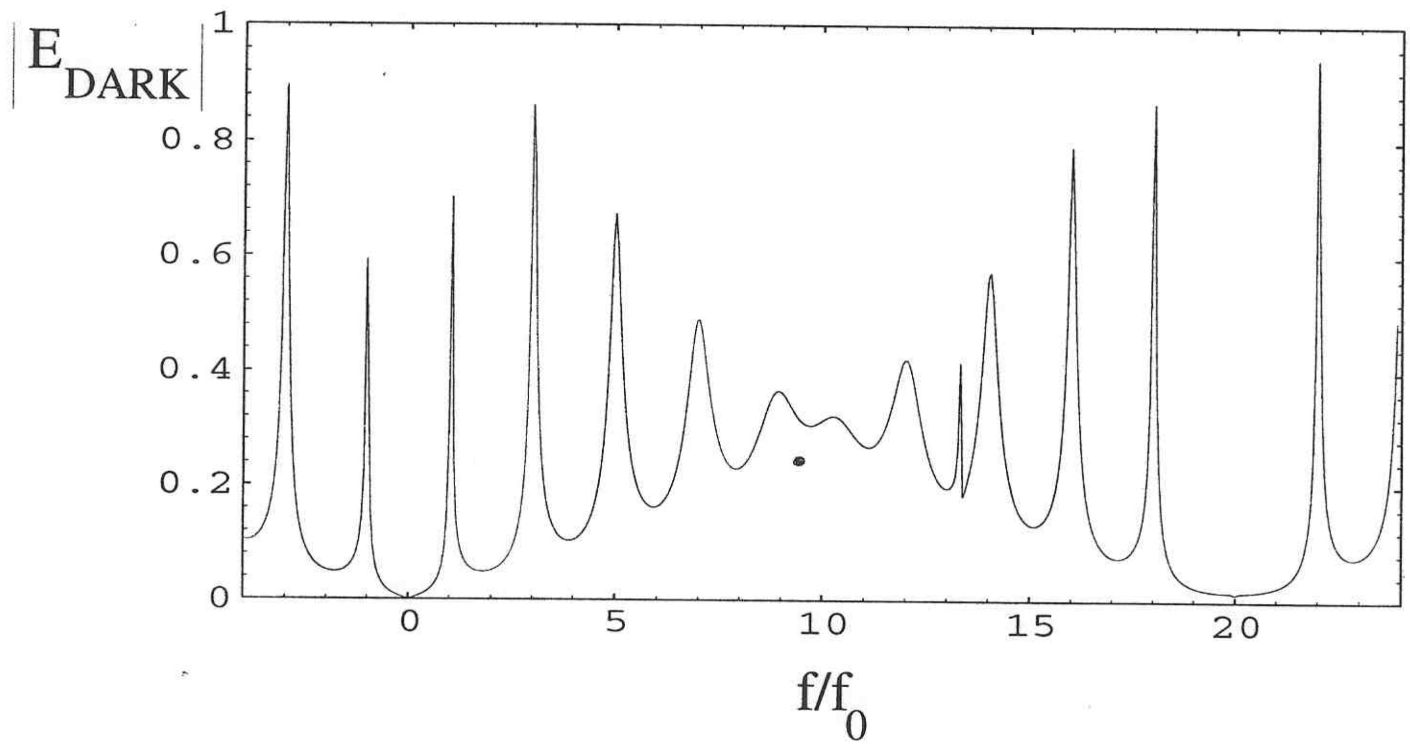


5
4
3
2
1
0
$|E_{RC}|$
0
5
10
15
20
f/f_0



|E_ARM|
f/f_0
0
1
2
3
4
5
0
5
10
15
20


|E_REFL|
1
0.8
0.6
0.4
0.2
0
5
10
15
20
f/f_0



|E_DARK|
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
f/f_0

IMPLICATIONS FOR LIGO

- Mode cleaner
- 4 km long arm cavities → $fsr_{ARM} = 37.5$ kHz
- 18 m long recycling cavity → $fsr_{RC} = 8.33$ MHz
- Dense population of modes
- Degenerate recycling cavity → stringent requirements due to mode overlap
- Develop an informed criterion for mode overlap tolerance
- ☐ Question of SCSB2
- Determine signal-to noise-ratios for shotnoise limited sensitivity to gravitational-wave signal
- Vacuum envelope
- Custom optics