LIGO advancedligo

AMALDI 8, 8TH EDOARDO AMALDI CONFERENCE ON GRAVITATIONAL WAVES COLUMBIA UNIVERSITY, NEW YORK JUNE 21-26, 2009

DCC # LIGO-G0900598-v1

CURRENT STATUS AND FUTURE PLANS FOR THE LIGO THERMAL COMPENSATION SYSTEM (TCS)

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INTRODUCTION

HIGH LASER POWER CREATES STRONG THERMAL LENSING IN THE INTERFEROMETERS OPTICAL RESONANT CAVITIES USED FOR GRAVITATIONAL WAVE DETECTION. MORE DEMANDING PERFORMANCE WILL REQUIRE EVEN HIGHER AMOUNT OF POWER STORED IN CAVITIES. TO BE ABLE TO CONTROL THE INTERFEROMETER AND ACHIEVE THE STORED POWER DESIGN, WE REQUIRE ACTIVE WAVEFRONT CORRECTION SYSTEMS TO MINIMIZE THE THERMAL LENSING.

THE INCREASED LASER POWER OF **ADVANCED LIGO** WILL NECESSITATE A TCS OF MUCH GREATER COMPLEXITY THAN THE CURRENT SYSTEM.

WE WILL DISCUSS THE RECENT IMPROVEMENT OF THE THERMAL COMPENSATION SYSTEM IN PREPARATION FOR THE NEXT LIGO SCIENCE RUN AND THE DESIGN OF THE THERMAL COMPENSATION SCHEME FOR ADVANCED LIGO.

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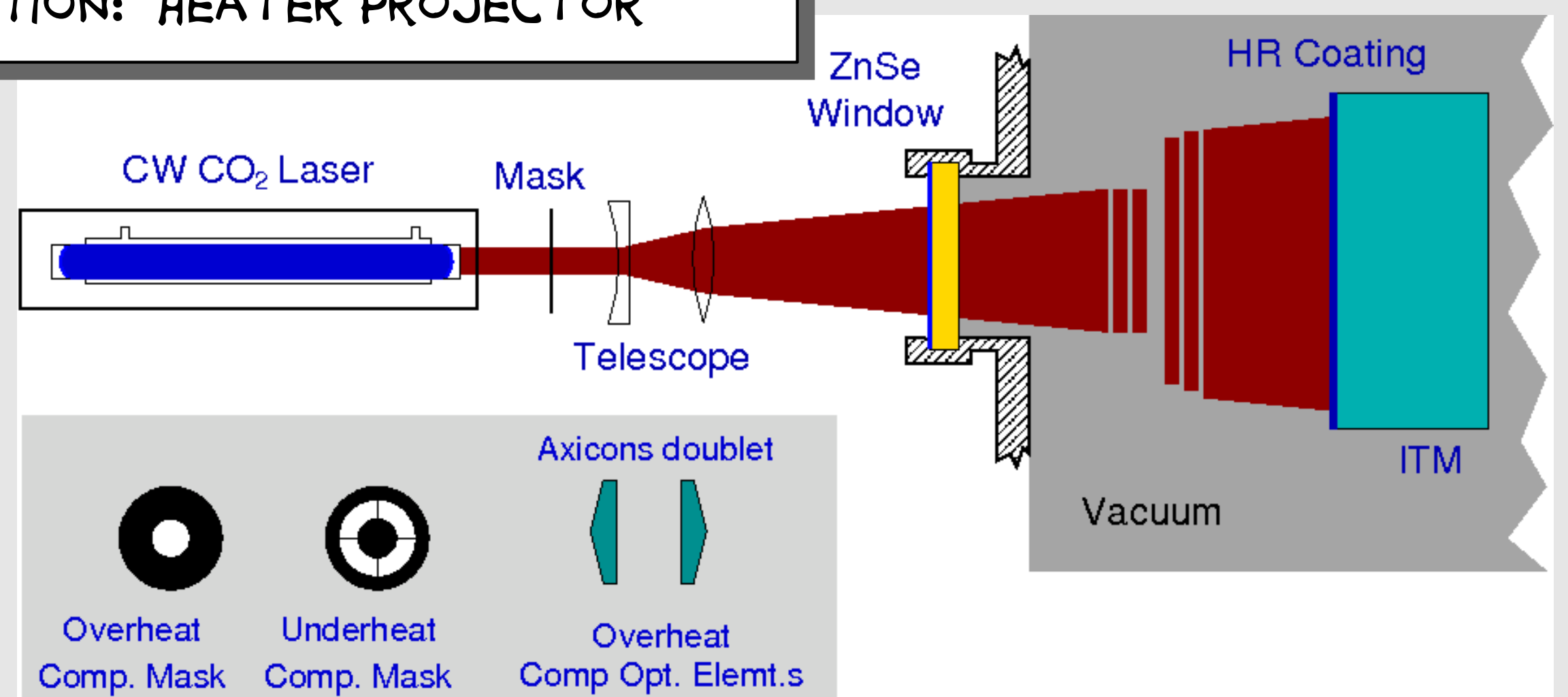
INTERFEROMETER THERMAL COMPENSATION: HEATER PROJECTOR



HOW IT WORKS

THE HEATING OF THE OPTICS SUBSTRATE PRODUCES A CHANGE IN OPTICS REFRACTIVE INDEX (MAIN EFFECT). THIS PHENOMENON TOGETHER WITH A CHOSEN HEAT DISTRIBUTION, ALLOW TO CREATE A THERMALLY CONTROLLED LENS (THERMAL LENSING.). USING A LASER BEAM TO HEAT THE MIRROR WITH THE APPROPRIATE TRANSVERSE POWER DISTRIBUTION WE CAN CONTROL THE EFFECTIVE CURVATURE OF THE MIRROR AND THEREFORE COMPENSATE FOR THE OPTICAL RESONANT CAVITY MISMATCH WITH THE INTERFEROMETER LASER BEAM WAVEFRONT. THE CO2 LASER WAVE LENGTH (10.6um) IS QUASI IDEAL BECAUSE OF THE SUBSTRATE AND HR COATING HIGH ABSORPTION COEFFICIENT (~ 90%).

INTERFEROMETER THERMAL COMPENSATION: NOISE MECHANISMS

THE CO2 LASER DEPOSITS HEAT JUST ON ONE FACE OF THE MIRROR. IF THE LASER POWER FLUCTUATES, THE HEAT DEPOSIT FLUCTUATES AND WILL CREATE DISPLACEMENT NOISE $<\Delta z>$ BECAUSE OF THE FOLLOWING COUPLING MECHANISM:

THERMO-ELASTIC NOISE (TEN) : HEAT PRODUCES CHANGES IN THE THERMAL EXPANSION OF THE MIRROR CHANGING THE MIRROR SURFACE.

THERMO-REFRACTIVE NOISE(TRN): THE REFRACTIVE INDEX DEPENDENCE WITH THE TEMPERATURE CHANGES THE OPTICAL PATH OF THE INTERFEROMETER.

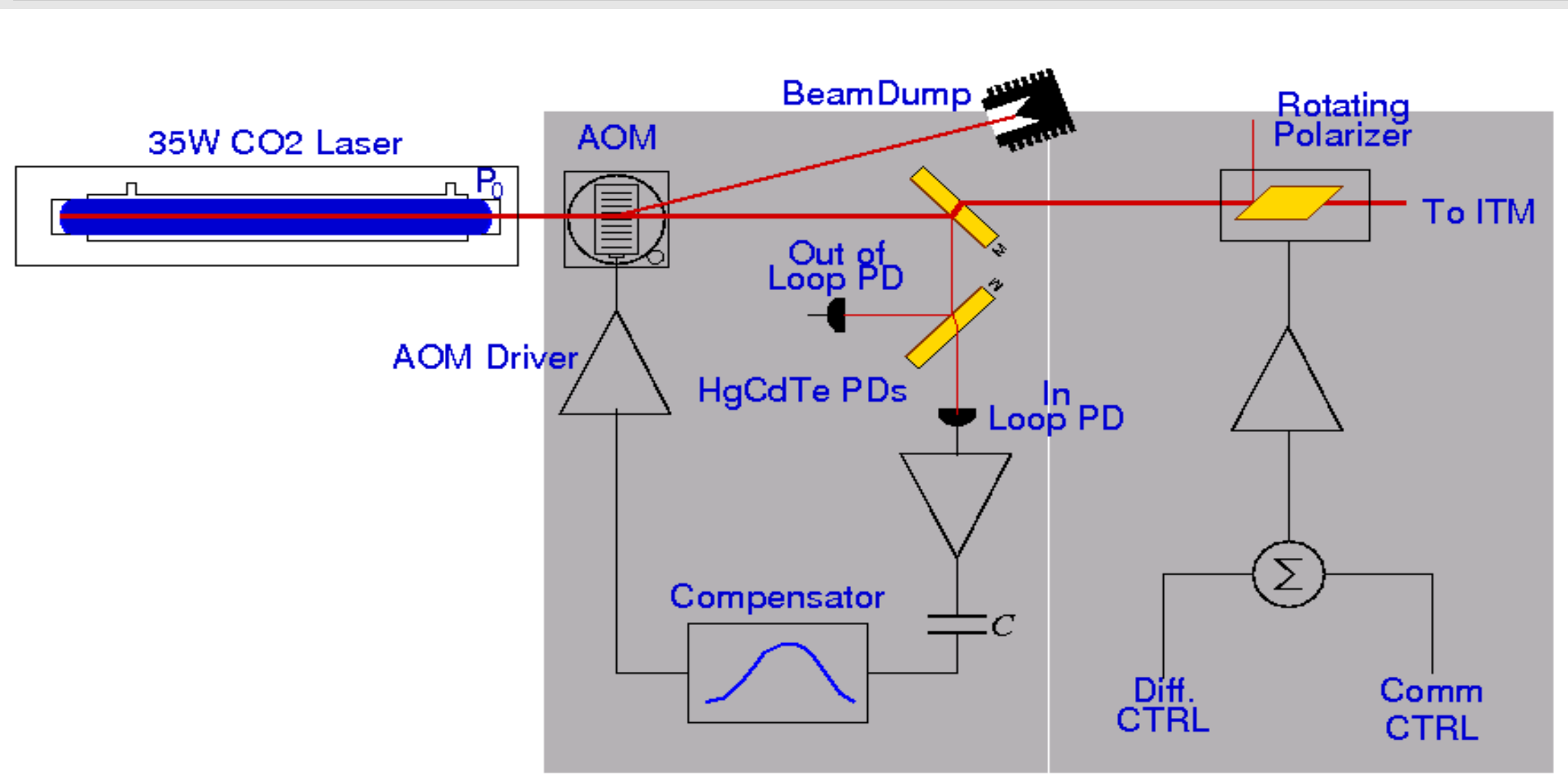
FLEXURE NOISE (FN): HEAT OF ONE FACE OF THE OPTICS PRODUCES AN UNEVEN THERMAL EXPANSION OF THE MIRROR WHICH CAUSES A CHANGE IN CURVATURE OF THE MIRROR

$$\langle\Delta z\rangle = \frac{P}{2\pi f C\rho}\left(\frac{1}{\pi w^2}\left[\underbrace{(1+\eta)\alpha\left(1-\frac{\pi}{2\mathcal{F}}(n-1)\right)}_{\text{TEN}} - \underbrace{\frac{\pi}{2\mathcal{F}}\frac{dn}{dT}}_{\text{TRN}}\right] + \underbrace{\frac{6\alpha}{h^2}C_{\text{num}}}_{\text{FN}}\right)\text{RIN}$$

P IS THE TCS AVERAGE LASER POWER, WITH THE SAME GAUSSIAN SPOT SIZE w AS THE IFO BEAM, ρ AND C ARE THE DENSITY AND HEAT CAPACITY OF FUSED SILICA, η IS THE FUSED SILICA POISSON RATIO, α THE THERMAL EXPANSION COEFFICIENT, n AND dn/dT THE INDEX OF REFRACTION AND ITS TEMPERATURE DEPENDENCE, F THE FINESSE OF THE ARM CAVITY, AND h THE THICKNESS OF THE INPUT TEST MASS . C_{nm} DESCRIBES THE THERMALLY INDUCED STRESS COUPLING MECHANISM. THIS FACTOR IS A MINOR CONTRIBUTION FOR CENTRAL HEATING BUT TENDS TO DOMINATE THE NOISE FOR ANNULAR HEATING, OF WHICH BARREL HEATING IS AN EXTREME CASE.

RIN IS THE RELATIVE INTENSITY NOISE WHICH IS THE REDUCED BY THE ISS SYSTEM.

INTERFEROMETER THERMAL COMPENSATOR; INTENSITY STABILIZATION SERVO (ISS)



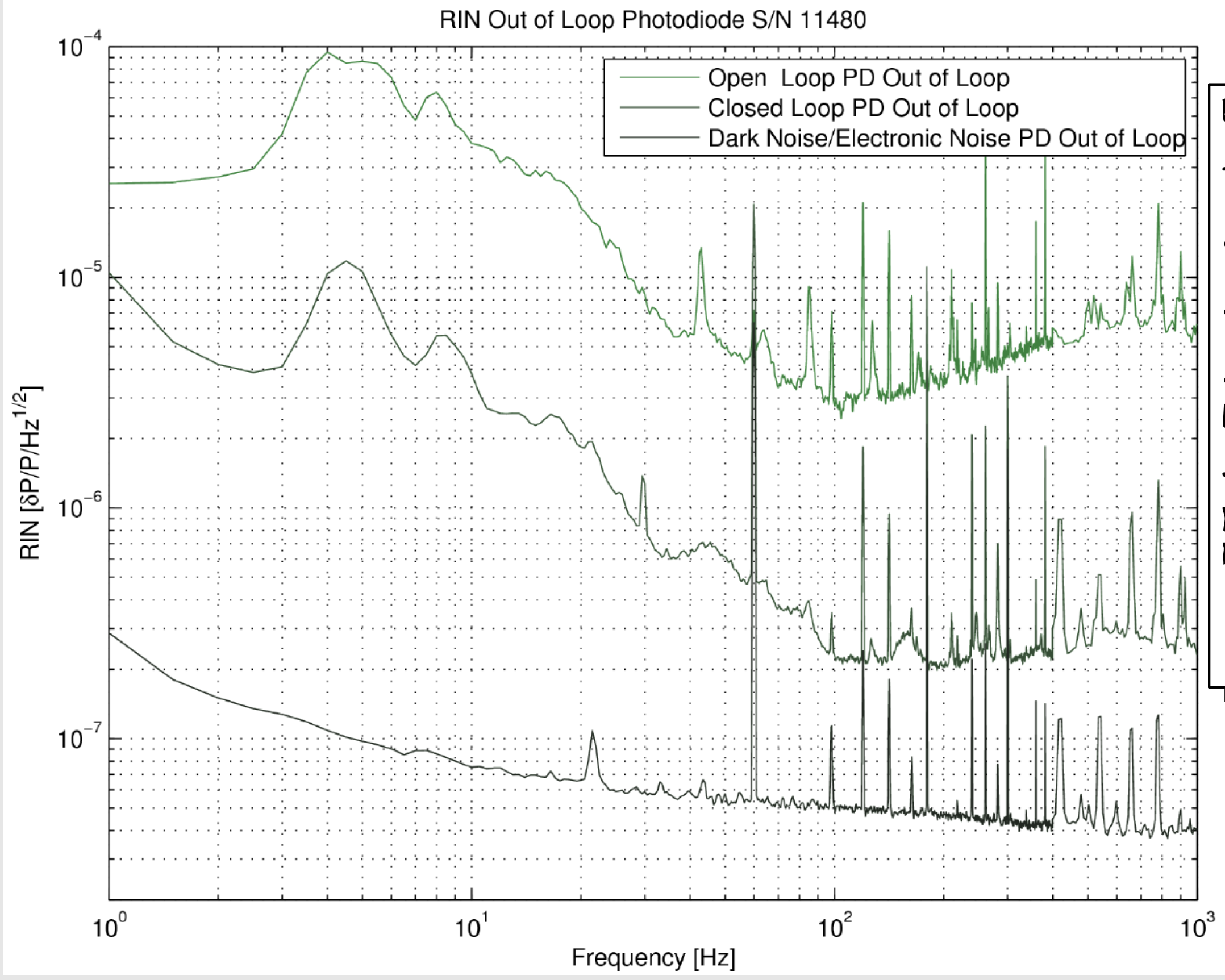
CURRENT PERFORMANCE ARE LIMITED BY THE PD PRE-AMPLIFIER VOLTAGE NOISE $\sim 1\text{nV}/\sqrt{\text{Hz}}$

SERVO BAND FROM ~0.1Hz to ~60kHz

SUPPRESSION FACTOR ~ 10-30

THE ACOUSTO-OPTIC-MODULATOR DEFLECTS 10-20% OF THE LASER LIGHT. A PERCENTAGE OF THE EMERGING LIGHT IS SAMPLED BY A HgCdTe PHOTO-DIODE (PD). THE PD SIGNAL CARRIES THE LIGHT POWER FLUCTUATION WHICH ONCE FILTERED TO SATISFY STABILITY AND PERFORMANCE CRITERIA IS SENT TO THE AOM MODULATOR. THE AOM CORRECTS THE LIGHT POWER FLUCTUATION BY INSTANTANEOUSLY DEFLECTING THE PROPER AMOUNT OF LIGHT. LOW FREQUENCY POWER DRIFT CAN BE CONTROLLED BY A BREWSTER ANGLE ROTATING POLARIZED.

INTERFEROMETER THERMAL COMPENSATOR: ISS PERFORMANCE

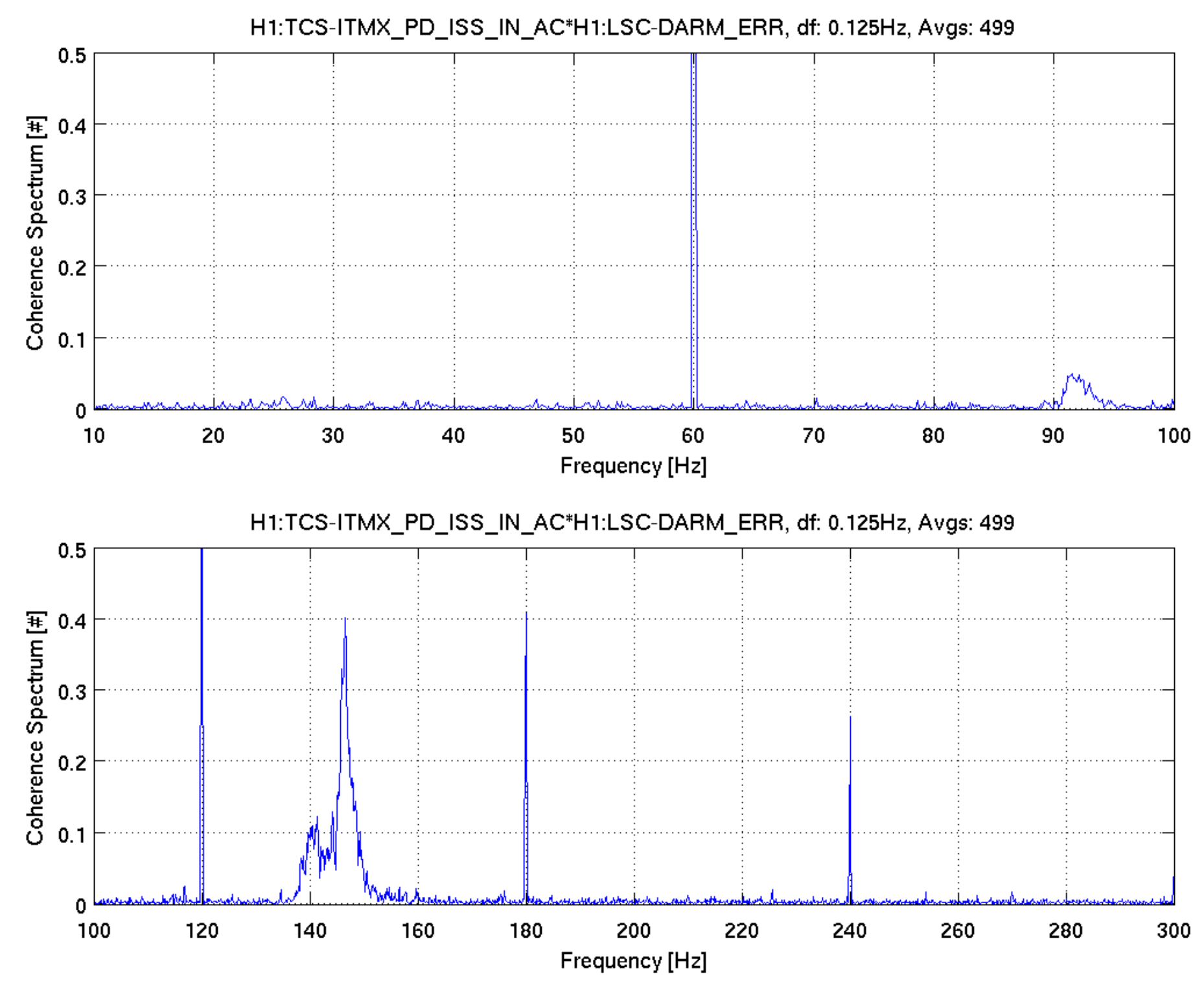


RELATIVE INTENSITY NOISE (RIN) OF THE OUT OF LOOP PHOTO-DETECTOR FOR THE FOLLOWING CASES:

- ISS LOOP OPEN, LIGHT, GREEN CURVE.
- ISS LOOP CLOSED, DARK GREEN CURVE.
- NO LIGHT IMPINGING ON THE PHOTO-DETECTOR, BLACK CURVE.

THE OUT OF LOOP PHOTO-DETECTOR PROVIDES THE RELIABLE SIGNAL TO ESTIMATE THE RIN.

COHERENCE SPECTRUM WITH DIFFERENTIAL ARM LENGTH SENSING SIGNAL



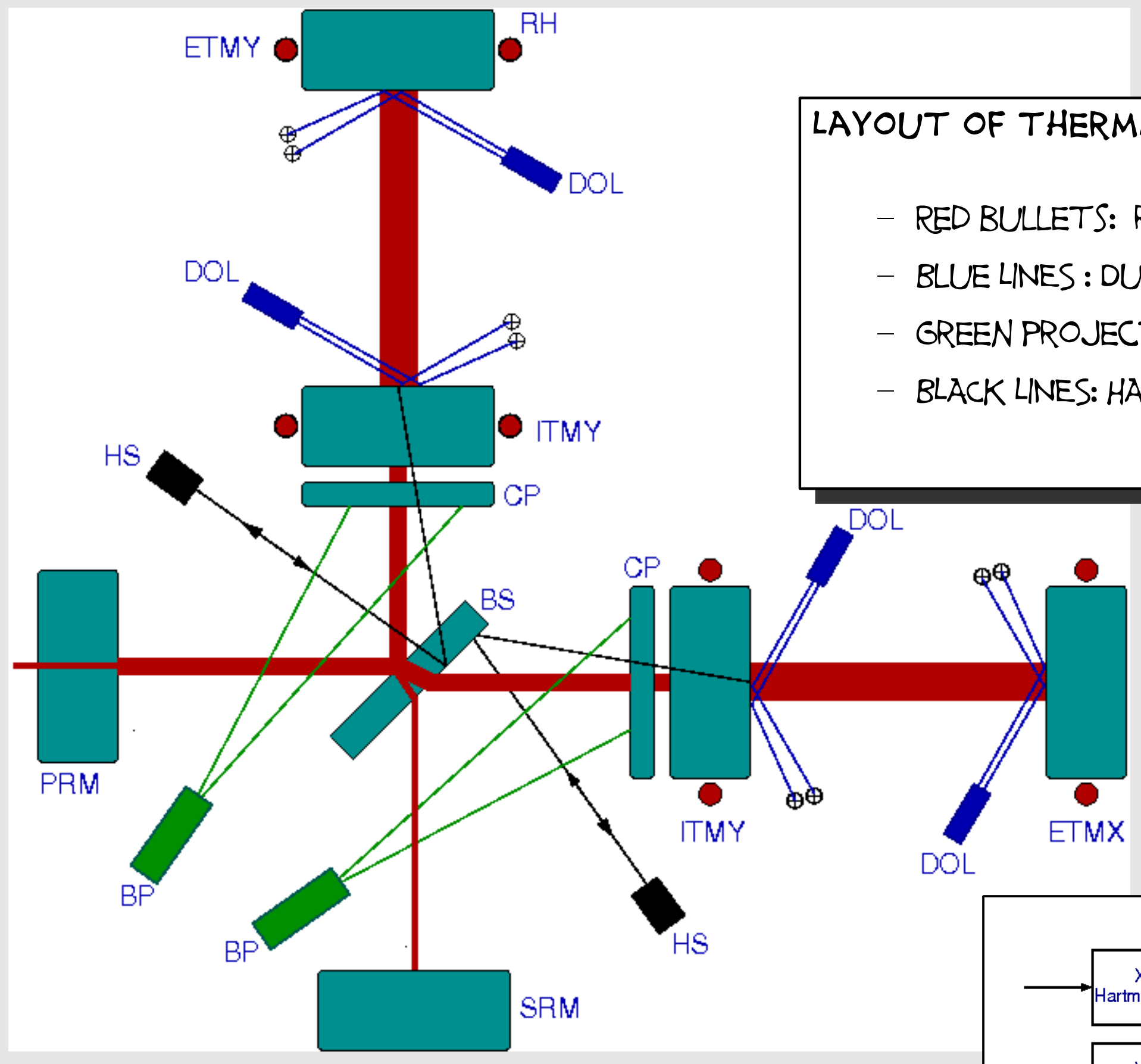
COHERENCE SPECTRUM BETWEEN THE ISS IN LOOP PD SIGNAL AND THE ERROR SIGNAL OF THE ARMS DIFFERENTIAL LENGTH USED TO CONTROL THE INTERFEROMETER'S FABRY-PEROT CAVITIES AND EXTRACT THE MAIN INTERFEROMETER SIGNAL.

APART FROM STRONG COHERENCE AT POWER LINES FREQUENCIES THE SPECTRUM SHOWS A RELATIVELY HIGH COHERENCE 0.4 AT 147Hz.

THE 147Hz PEAK IS DUE TO A TYPICAL INTENSITY NOISE INJECTION MECHANISM: IF THE LASER BEAM IS CLIPPING ON AN OPTIC EXCITED BY A MECHANICAL RESONANCE IT WILL GENERATE INTENSITY NOISE. COHERENCE WITH THE PD IS DUE TO THE EXCITATION OF THE PD AND THE NON UNIFORMITY RESPONSE OF THE PD'S ACTIVE AREA.

A MORE CAREFUL BEAM ALIGNMENT ELIMINATED THE COHERENCE @ 92 and 147Hz

ADVANCED LIGO: THERMA COMPENSATOR LAYOUT & CONTROL STRATEGY



LAYOUT OF THERMAL COMPENSATION SYSTEM.

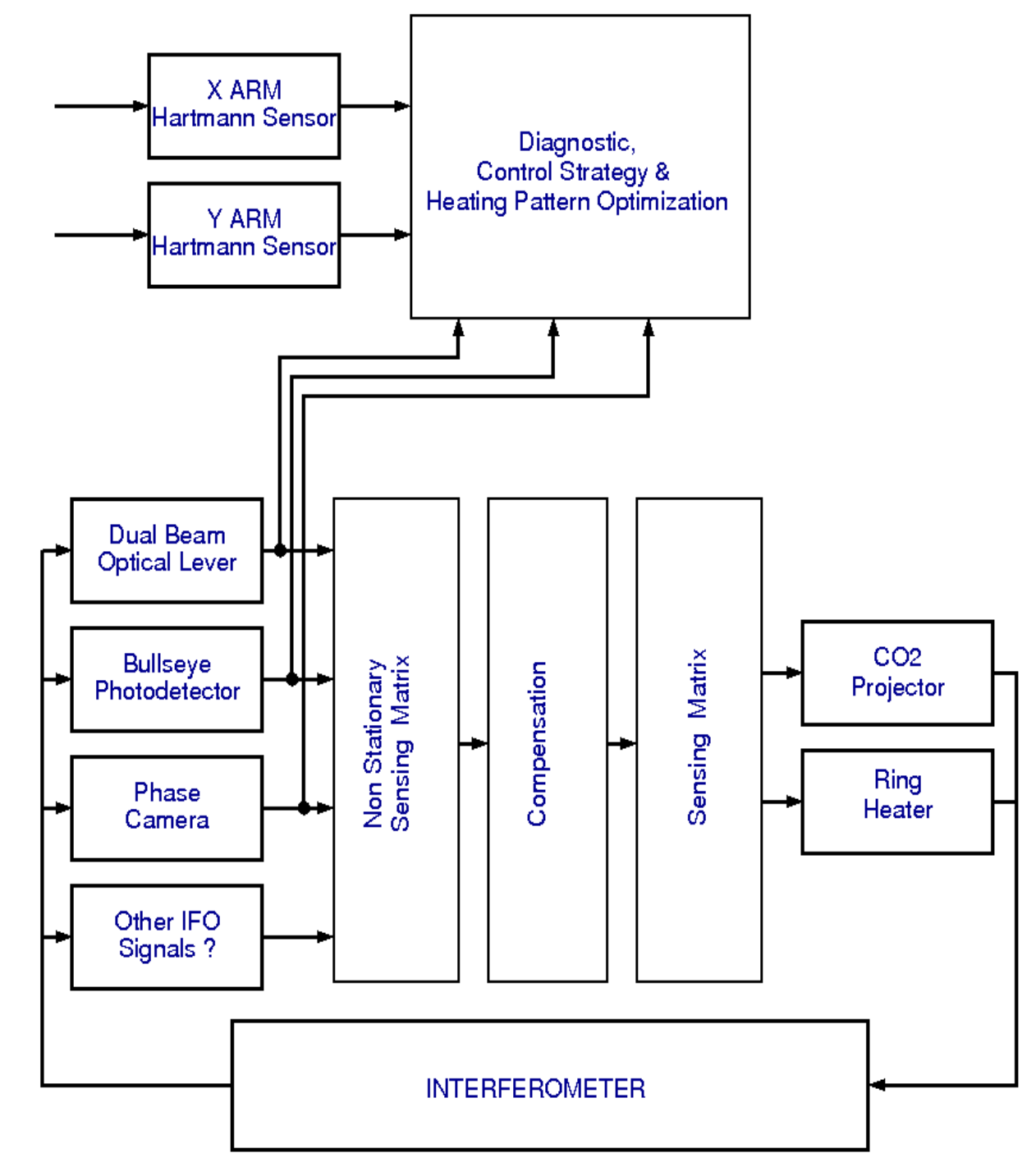
- RED BULLETS: RING HEATERS,
- BLUE LINES : DUAL OPTICAL LEVER SENSORS,
- GREEN PROJECTIONS: CARBON DIOXIDE LASER HEATERS.
- BLACK LINES: HARTMANN SENSORS.

THERMAL COMPENSATION CONTROL

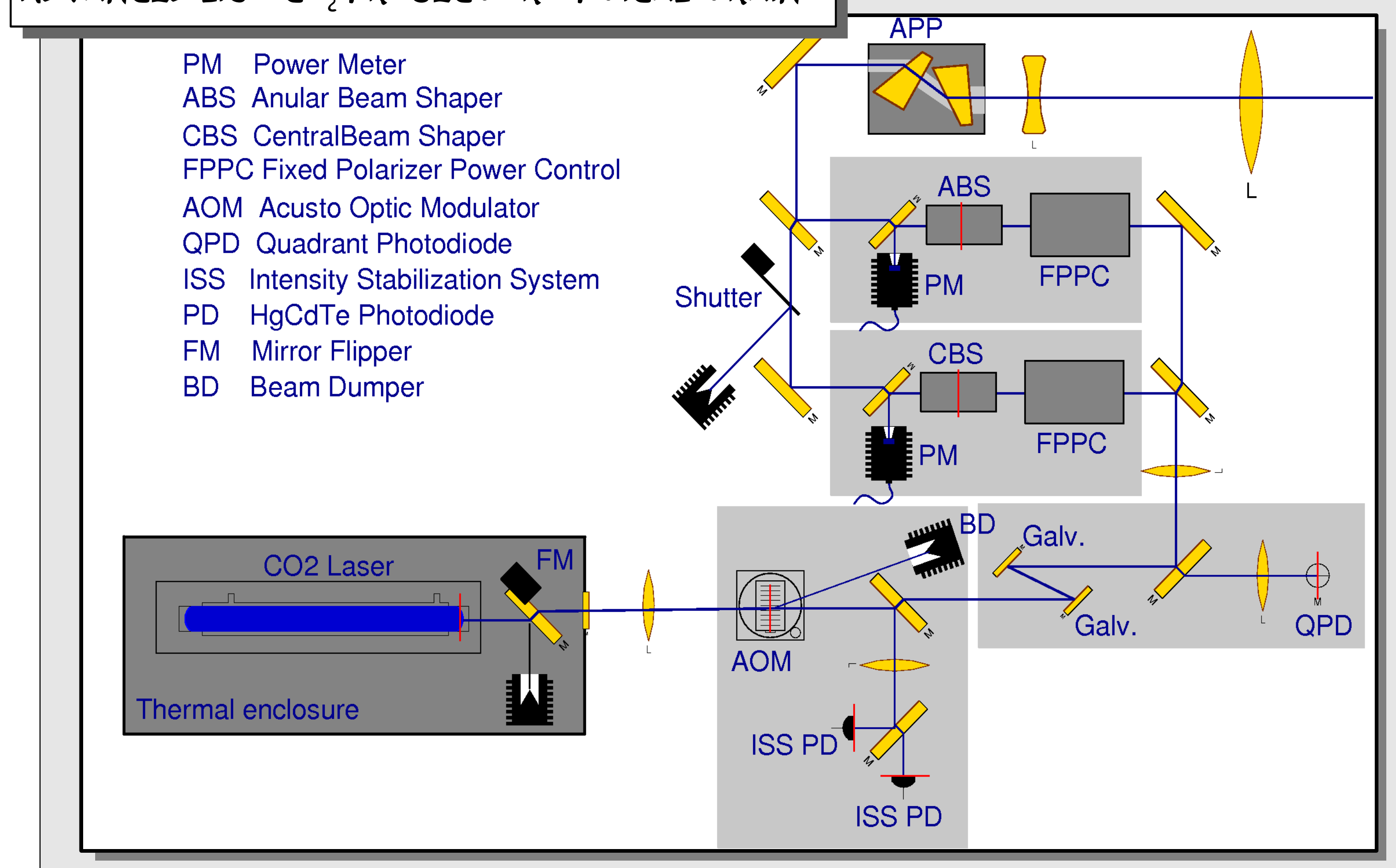
DIRECT MEASUREMENT AND STUDY OF THE INTERFEROMETER SIGNAL ARE REQUIRED TO DEVISE A ROBUST CONTROL LAW FOR THE INTERFEROMETER THERMAL COMPENSATION.

THE MAIN SENSOR SIGNALS ARE THE BULLSEYE PHOTO-DETECTORS WHICH MEASURE THE SIDE BANDS INTENSITY USED TO CONTROL OF THE INTERFEROMETER LONGITUDINAL DEGREES OF FREEDOM AND THE PHASE CAMERAS WHICH ALLOW TO MEASURE THE WAVEFRONT OF THE MAIN BEAMS EMERGING FROM THE INTERFEROMETER.

THE NON STATIONARITY OF THE INTERFEROMETER WILL PROBABLY REQUIRE TO MEASURE THE SO CALLED SENSING MATRIX DYNAMICALLY TO ACCOUNT THE DRIFT IN THE INTERFEROMETER RESPONSE.



ADVANCED LIGO CO$_2$ PROJECTOR OPTICAL TRAIN



PM	Power Meter
ABS	Anular Beam Shaper
CBS	CentralBeam Shaper
FPPC	Fixed Polarizer Power Control
AOM	Acusto Optic Modulator
QPD	Quandrant Photodiode
ISS	Intensity Stabilization System
PD	HgCdTe Photodiode
FM	Mirror Flipper
BD	Beam Dumper

LAYOUT OF THE CO$_2$ LASER PROJECTOR FOR ADVANCED LIGO. THE LASER IS THERMO-STABILIZED TO 0.05K WITH AN ACTIVE THERMAL INSULATION ENCLOSURE. THIS LIGHTPROOF AND ACOUSTIC ENCLOSURE ALSO ALLOWS TO "DE-CLASS" THE 35W LASER TO CLASS I THANKS TO A MIRROR FLIPPER WHICH CAN DUMP MOST OF THE POWER TO A WATER COOLED BEAM DUMP.

FOLLOWING THE OPTICAL TRAIN FROM THE LASER OUTPUT WE FOUND:

- THE INTENSITY STABILIZATION SERVO OPTICAL ELEMENTS (ISS),
- THE ANGULAR JITTER REDUCTION SYSTEM (AJR),
- THE FIXED POLARIZATION ANULAR AND CENTRAL HEATING CONTROL SYSTEM (FPCH & FPAH),
- THE BEAM IMAGE CIRCULARIZER ON TEST MASS FACE (BIC),
- THE MAGNIFYING TELESCOPE (MT).

ISS : THE ISS SYSTEM USES A WATER COOLED AOM AS THE ACTUATOR AND TWO HgCdTe PHOTO-DIODES (IN AND OUT LOOP) SENSORS.

AJR : THE AJR SYSTEM USES A PAIR OF GALVANOMETERS AS ACTUATORS AND A HgCdTe QUADRANT PHOTODIODE TO MINIMIZE THE BEAM ANGULAR JITTER.

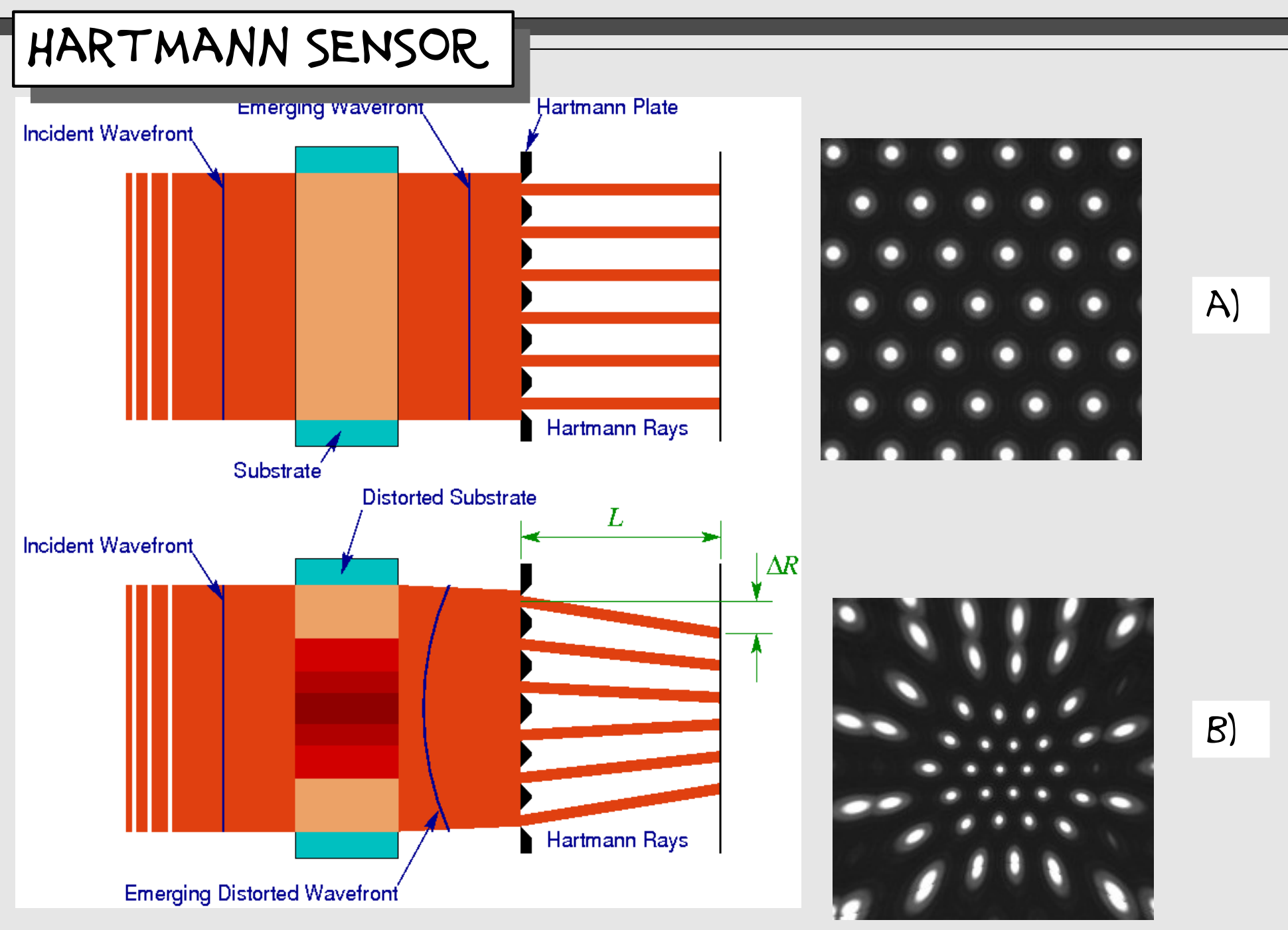
FPCH & FPAH: THE POWER CONTROL OF THE CENTRAL AND ANULAR HEATING IS DONE USING A REMOTELY CONTROLLED ROTATING HALF WAVE PLATE WITH A FIXED BEAM SPLITTER POLARIZER TO REDUCE ANGULAR JITTER INDUCED BY ROTATING POLARIZERS.

BIC: CIRCULARIZATION OF THE BEAM IMAGE ON THE TEST MASS FACE WITH LARGE INCIDENT ANGLES IS OBTAINED USING AN ANAMORPHIC PRISM PAIR WHICH CAN TURN THE TRANSVERSE BEAM PROFILE ELLIPTIC.

MT: MAGNIFYING TELESCOPE LAUNCHES THE BEAM IMAGES AT THE **ABS** AND **CBS** TO THE COMPENSATING PLATE FRONT FACE PLACED IN FRONT OF EACH ITM MIRRORS.

THIS DESIGN IS BASED ON LESSON LEARNED FROM THE CURRENT ENHANCED LIGO CO$_2$ PROJECTOR AND ALSO CONTAINS ELEMENTS OF THE CURRENT VIRGO TCS PROJECTOR.

HARTMANN SENSOR



HOW IT WORKS

A) HARTMANN RAYS PROPAGATE NORMAL TO THE INCIDENT WAVEFRONT TO THE HARTMANN PLANE .

B) IF THE WAVEFRONT SLOPE CHANGES THE SPOT POSITIONS SHIFT.

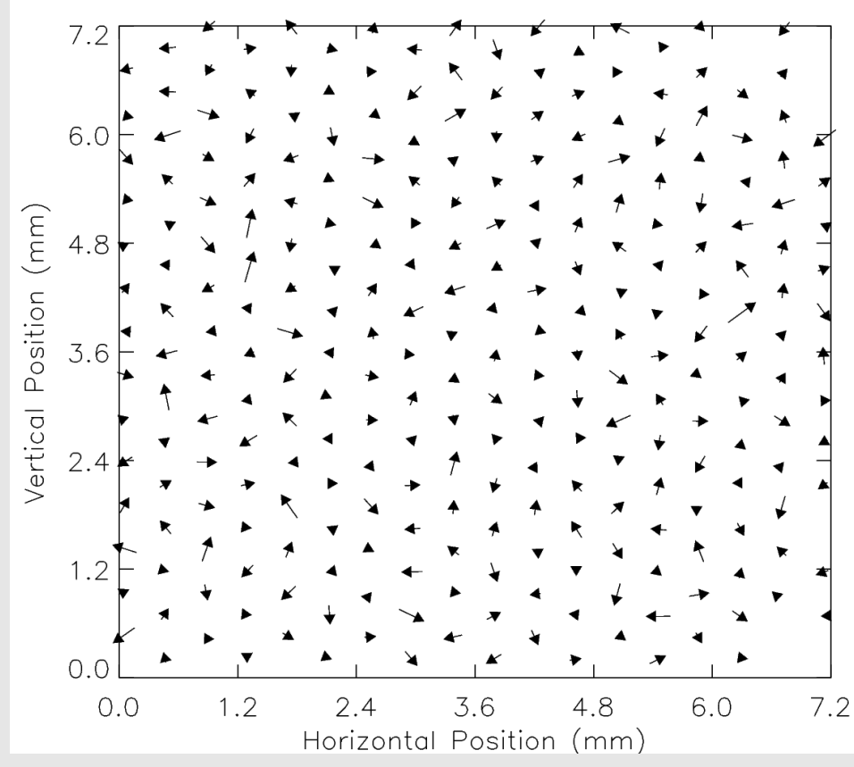
THE SHIFT IS PROPORTIONAL TO THE WAVEFRONT PHASE SHIFT $\Delta\varphi$, I. E.:

$$\Delta\varphi = \Delta r/L$$

A CDD CAMERA COLLECTS THE IMAGE TO COMPUTE THE PATTERN CHANGE WHICH IS THEN USED TO RECONSTRUCT THE WAVEFRONT $w(x,y)$.

DEMONSTRATED WAVEFRONT RESOLUTION

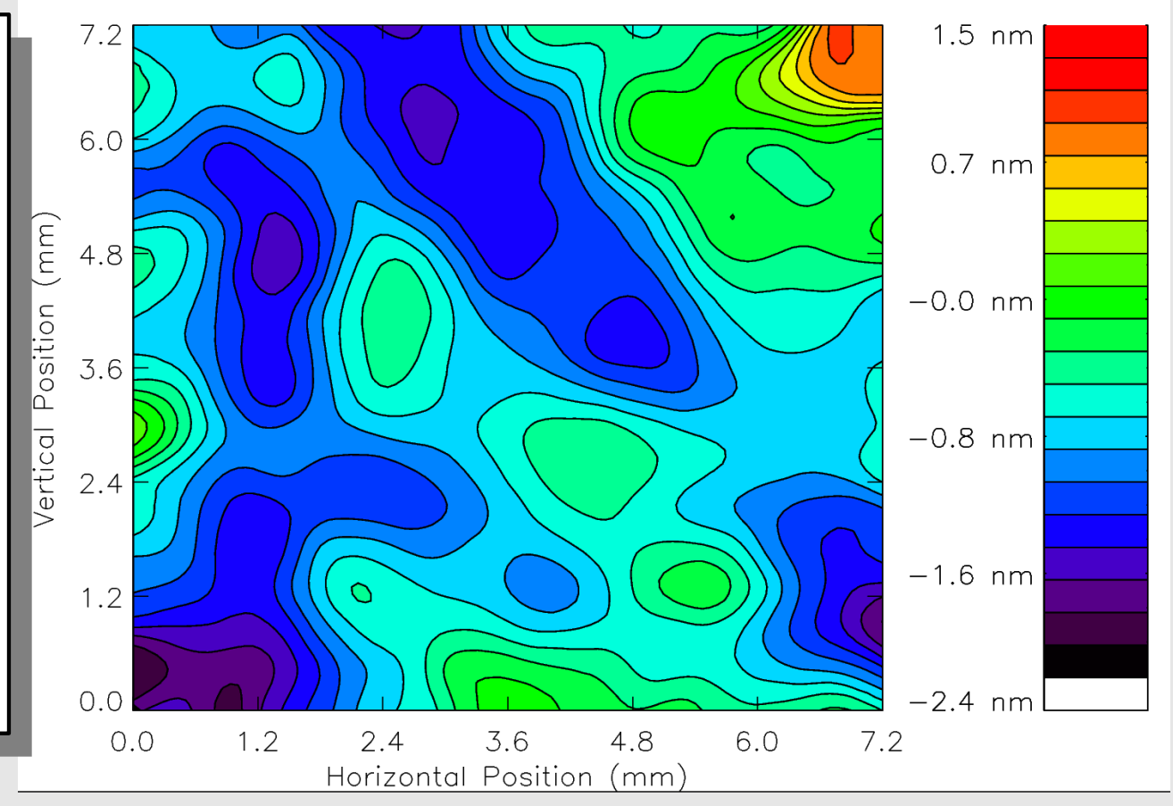
$$\sigma_w = \lambda/500$$



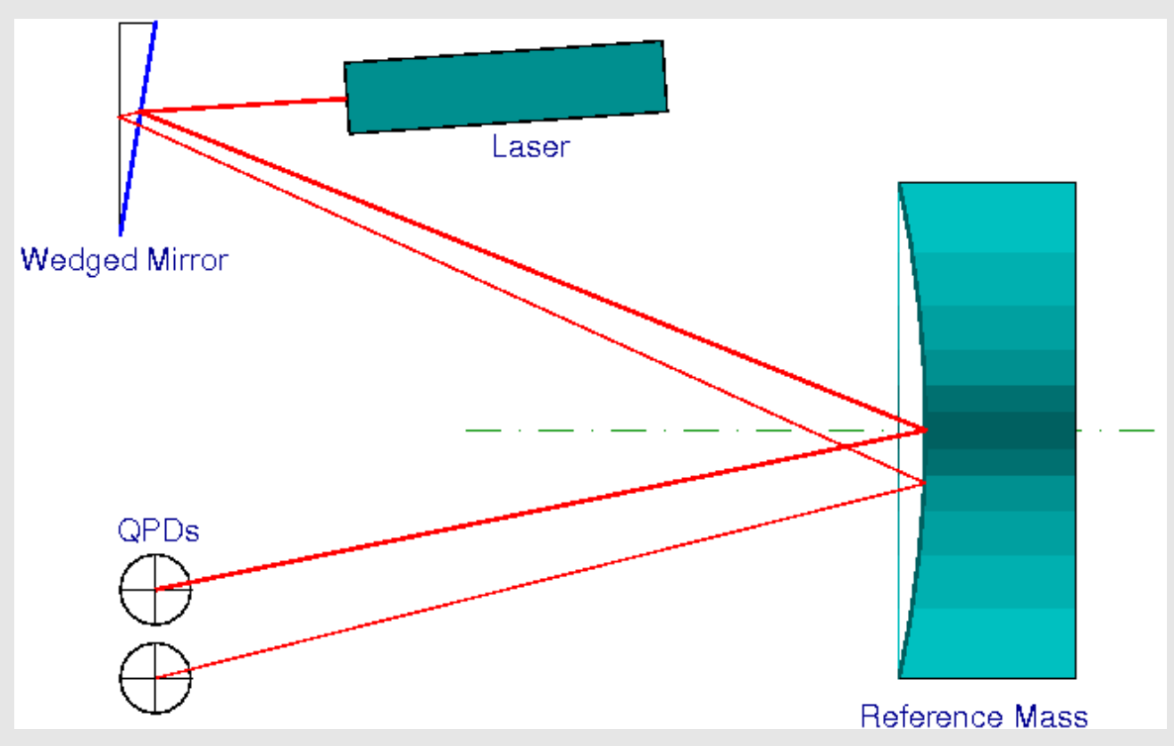
HARTMAN SENSOR NOISE FLOOR

THE DIFFERENCE OF TWO ACQUIRED CONSECUTIVE PATTERNS OF THE WAVEFRONT OF AN INCOHERENT POINT-LIKE SOURCE IS A MEASURE OF THE HARTMANN SENSOR NOISE FLOOR (LEFT FIGURE).

THE RECONSTRUCTED WAVEFRONT IS THEREFORE THE WAVEFRONT SPACIAL RESOLUTION OF THE SENSOR (RIGHT FIGURE)



DUAL BEAM OPTICAL LEVER



HOW IT WORKS

THE DOUBLE BEAM OPTICAL LEVER CAN ESTIMATE THE VARIATION OF THE RADIUS OF CURVATURE ΔR DUE TO THERMALLY INDUCED STRESS.

ONE BEAM IMPINGES AS CLOSE AS POSSIBLE TO THE CENTER OF THE MIRROR MAKING THE REFLECTED BEAM QUITE INSENSITIVE TO CURVATURE CHANGES. THE SECOND BEAM WILL THEN MEASURE ΔR .

MIRROR TRANSLATION AND TILTS CAN BE SUBTRACTED TO A CERTAIN DEGREE BECAUSE THEY CREATE MAINLY A COMMON MODE SIGNAL IN THE TWO QUADRANT PHOTO-DETECTORS OUTPUT.