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OUTLINE OF A PROPOSED DESIGN FOR A FIRST RECEIVER FOR INSTALLATION IN THE LONG-BASELINE FACILITIES, OF FABRY-PEROT TYPE

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1. GOALS OF THE DESIGN.

The design intends to achieve the following aims, as far as possible:-

(a) A reasonable compromise between maximum designed sensitivity and avoidance of risk of failure due to excessive dependence on untested technologies.

(b) Design of a relatively simple "Base Model" intended to easily achieve a satisfactory and potentially useful performance for initial operation, but designed also for future enhancements by addition of further components, increasing laser power, etc., to form a variety of compatible future "Upgrades" from which a planned succession of receivers can be chosen. In addition, the possibility of some "Downgrades" from the Base Model is also taken into account, in case development becomes delayed, unexpected problems arise, or cost restrictions force cutbacks in initial performance.

(c) A receiver design which is as compatible as possible with other receivers which may share the vacuum system and operate concurrently. The objective of using or obscuring a minimum area of the cross section of the vacuum pipe has thus been an important factor in the design, so that the maximum number of other receivers, which may have test masses located either behind or in front of its own test masses, may be operated with it. Design choices giving minimum cross sectional area have been adopted wherever possible.

(d) A basic receiver design capable of being realized and enhanced in a way which is economical both in construction cost and in design effort. To this end the construction of the receiver is made modular as far as possible, with most elements common throughout the different versions and upgrades or downgrades. This should allow economies in design effort, and facilitate small-scale quantity production of the main units so that cost and effort required eventually to put into

*Based on Draft 2 of August 26, with additions on laser source system and corrections.

operation several receivers covering different gravitational wave experiments will be minimized. Also common components are used as far as possible for various functions within any one interferometer, so that items such as test mass blanks and many suspension components can be ordered in quantity - possibly in numbers of the order of 20 or more for one interferometer, and in larger quantities for the full LIGO system.

(e) A receiver system capable of operation over extended periods without manual adjustment. A totally automatic alignment control system is an important feature of the design, as it is felt that this will become an essential operating requirement with any type of interferometer having kilometer-long lever arms in the optical beams. A manual alignment system is however also provided for early test purposes, and as a backup which comes automatically into operation in case of disruption by excessive seismic noise, loss of servo lock, equipment malfunction, or other types of failure.

(f) A further aim of the design is a receiver for operation over kilometer baselines which is capable of being as effectively tested as possible using the much shorter baselines of existing prototype facilities. The receiver is designed to operate over short baselines as well as long ones, with minimal changes. The only significant modification for operation over a short baseline will be the use of cavity mirrors (and some other optical components) of smaller radius of curvature than for the kilometer system and, for certain tests, having coatings of different reflectivity. Of course operation over 40-meters can never exactly duplicate operation over 4 kilometers, but the achievement of millisecond light storage times in the 40-meter prototype interferometer indicates the feasibility of exploring effectively many aspects of the operation of a full-scale Fabry-Perot receiver in a prototype vacuum system, in part by combining data obtained in tests with mirror coatings of different reflectivities.* Some phenomena (such as scattering from pipe walls) do intrinsically require long beam pipes and will be difficult to study in advance, but we would like to check as much as possible. This "testability" of the proposed receiver is an important aspect of the design. It may enable us to get valuable practical experience in operation of the interferometers and associated data systems long before the construction phase of the large vacuum facilities is

*One type of receiver test, for example, can be made with cavity mirrors having reflectivity similar to those of the present 40-meter prototype, so that light storage times comparable to those planned for the 4 kilometer system (of order 1 millisecond) will be achieved. Under these conditions, the large number of reflections in each arm can in principle give a Fabry-Perot interferometer a much better photon-shot-noise-limited displacement sensitivity over 40 meters than it (or any other interferometer using the same light power) would have over 4 kilometers. Thus measurements of thermal noise, suspension noise, and seismic isolation can be made extremely sensitive over a prototype-scale baseline with a suitable-designed Fabry-Perot receiver - in fact they can be much more critical and sensitive than ever likely to be required for kilometer-baseline operation. This feature of a Fabry-Perot system may prove to be a valuable asset in future development towards higher sensitivity. Another mode of test operation is with mirror coatings of the same reflectivity as those planned for kilometer baselines. In this mode tests and development of certain other aspects of receiver operation, such as phase measurement sensitivity and light recycling, can be effectively carried out.

complete and may facilitate achievement of another aim - a rapid and efficient shift from prototype operation to real full-scale gravity-wave searches as quickly as possible after access is gained to the large vacuum facilities.

(g) A general aim is to maximize the probability that the receiver when built will actually operate as planned, and in particular to design an interferometer which will be as immune as practicable to unpredicted phenomena which might reduce sensitivity. To this end the interferometer is designed to hold as constant as possible parameters which otherwise might conceivably introduce noise at frequencies near the gravity wave frequency region. Parameters which are controlled and maintained constant at relevant frequencies in this design include laser beam frequency, intensity, diameter, divergence and spectral composition; beam direction and position parameters in each arm relative to the positions of the test masses; and test mass translational and rotational coordinates. (Differential forces required to maintain the relative distances between the pairs of test masses in each arm constant are recorded as a measure of the gravitational wave.) Precautions taken in the design to control some of the parameters do go further than experience so far with prototype interferometers has shown to be absolutely essential, and it is quite likely that it may later be found to be unnecessary to control all of them as well as is provided for. However building in this control gives additional insurance against quite large classes of unpredicted phenomena.

2. SUMMARY OF CHARACTERISTICS OF THE BASE MODEL RECEIVER, AND PLANNED UPGRADES AND DOWNGRADES.

Consideration of the goals listed above has led to a design in which initial operation of the basic interferometer is planned with light from a single argon laser, though possibly with additional argon lasers available as backup. This approach requires minimal extension over present prototype operation. Recycling is proposed as a means of achieving good sensitivity with this relatively low power input, as it is judged that operation in a recycling mode will be easier and have less risk of failure than adding lasers together or use of NdYag lasers. (It may be noted here that successful recycling has already been demonstrated by both the Max-Planck and Orsay groups with simple interferometers: while if NdYag lasers were used it would be necessary to employ frequency doubling to keep within the wavelength region that has been demonstrated to give high interferometer sensitivity and in which we have extensive and good experience - and successful operation of a sensitive interferometer with a stabilized frequency-doubled NdYag laser of the required power output has not yet been demonstrated.)

Two versions of the Base Model are contemplated: Version 1, currently proposed as the first interferometer, intended for broadband searches; and Version 2, envisaged as likely to be the later unless there is some unexpected development in source expectations or detector technology, optimized for narrowband operation. Proposed main characteristics of these and of their upgrades and downgrades follow.

*(a) **Base Model, Version 1 (Broadband).***

(1) Light source - one single-mode argon ion laser, giving 5 to 6 watts output at 514 nm. (e.g. Coherent Innova or Spectra-Physics large-frame lasers of nominal all-line power 20 watts).

(2) Test Masses: Fused Silica, 8 inches diameter by 5 inches long, with ultra- low-loss mirror coating over the front surface giving a minimum usable area 5.5 inches in diameter.

(3) Test mass suspension giving primarily passive seismic isolation, but with a slaved active antiseismic system using an auxiliary interferometer to make seismic motions of the suspension points at opposite ends of each arm track one another.

(4) Wideband optical recycling is employed to increase effective light power.

(5) Broadband operation is envisaged, with useful sensitivity over the range from below 100 Hz to above 5 kHz.

*(b) **Base Model, Version 2 (Narrowband).***

Almost all main components are identical to those of Version 1, but some of the internal optics are modified to give resonant recycling for optimized narrowband searches. (Details specific to the narrowband versions of the receiver can be provided if requested.)

*(c) **Upgrade 1.***

Either version as above, or with Upgrades 2 or 4, but with light power increased to 20 watts by use of four argon lasers with their outputs added together coherently. This would be expected to improve sensitivity by a factor of 2 at the higher frequencies.

*(d) **Upgrade 2 (Sketched in Figure 5).***

Addition of active antiseismic guard system along three axes of the test masses near the junction of the arms, and along the transverse and vertical axes of the test masses at the remote ends of the arms. This can be applied to any of the versions or upgrades.

(e) Upgrade 3.

Replacement of the argon laser light source by a NdYag laser system with frequency doubler giving 100 watts of stabilized green light. This would be expected to improve sensitivity over that of Upgrade 1 by a factor slightly more than 2 in the high frequency region, and reduce electric power consumed.

(f) Upgrade 4.

Increase the size of the test masses to 1 ton by bonding the smaller test masses with their low-loss mirror coatings to the front of larger fused silica masses, using optical contacting. This is a modification which may extend low frequency performance at some possible penalty in high frequency performance, so is more likely to be used as another concurrently-operating receiver than as a change to the Base Model.

(g) Upgrade 5.

Use of squeezed-light techniques. A probably-late addition to improve performance of the broad-band model receivers.

Two possible Downgrades have been considered:

(h) Downgrade 1.

The Base Model, Version 1, without recycling.

(i) Downgrade 2.

The Base Model without the slaved active antiseismic system.

3. MAIN SUBSYSTEMS OF THE RECEIVER.

(a) Beam Generating and Conditioning System

(b) Beam Interfering System

(c) Suspension and Seismic Isolation System

(d) Alignment and Control Systems

 (1) Manual
 (2) Automatic

4. DESCRIPTION OF ASPECTS OF THE RECEIVER DESIGN.

The design and operation of the interferometer and its automatic alignment and beam centering system are intimately connected with the operation of the seismic isolation system, and some aspects of the design philosophy of the complete integrated receiver may be made clearer by beginning the description with an outline of the seismic isolation technique.

(a) Seismic Isolation - Base Model.

The primary isolation for the Base Model design is passive, and the main mass suspension inside the vacuum enclosure is in essence identical to that already well established in the 40-meter prototype (and also in the 10-meter interferometer at Glasgow). Experimental studies with the 40-meter prototype system have indicated that at the proposed interferometer sites it will almost certainly give by itself more than adequate isolation against direct seismic noise at all frequencies above about 100 Hz. A major part of the isolation here is given by five-layer lead and rubber stacks, and the only changes are to improve high-vacuum compatibility by encapsulating the individual rubber pads in very compliant sealed metal bellows (such as made by Hydraflex) and by replacing the layers of lead by layers of stainless steel. As in the present 40-meter system, the design has provision for air suspensions outside the vacuum system to assist in low frequency isolation.

Arrangements for damping the seismic pendulum motions of the test masses in the Base Model are essentially similar to those already used in the 40-meter prototype or currently being installed there. To improve low frequency isolation auxiliary interferometers, as currently being installed in the prototype, are arranged to monitor differential motions of the mass suspension points along each arm. These operate servo systems designed to make the suspension points at the stations distant from the central station track motions of the central ones. The arrangement is indicated schematically in Figure 1.

The four test masses have certain of their pendulum degrees of freedom damped to their local mounting baseplates (on the isolation stacks), using LED/photodiode shadow sensors (known as the "shark detectors" at Caltech) to monitor relative motion, with piezoelectric feedback to the suspension blocks for motions in the direction of the arm - as in the prototype. Some additional vertical compliance in the suspension will be introduced by incorporating a spring in the wire supporting each suspension block, and vertical and horizontal motions of the mass transverse to the beam direction are also monitored, and horizontal and vertical damping provided by magnetic feedback to the block.

An important feature of the design is that the four test mass suspensions are not operated as independent units. One test mass is regarded as the "master" mass - labelled A in the figures - and this is taken to define an effective inertial frame for the whole system, for motions in the directions of the main beams. The suspension points for the other masses are slaved to this master one using signals provided by the main and seismic interferometers, aided at low frequencies by a "beam centering unit" which can monitor the position of the main interferometer beam relative to the center of the cavity mirror attached to the test mass. Relevant degrees of freedom of each test mass suspension are controlled as follows. (See Figure 1.)

Mass A. The Master mass. Damped to local ground (suspension baseplate) in longitudinal, horizontal, and vertical directions by control of suspension block by shadow monitor signals - otherwise free for translational motion. (Rotational degrees of freedom for this and the other masses are separately controlled by the automatic alignment system, as will be outlined later.)

Mass B. A Slave mass. Longitudinal degree of freedom of the suspension block forced to track motion of the suspension block for mass A, using the seismic monitor interferometer. Transverse motions of the mass in horizontal and vertical directions relative to local ground damped by moving the suspension block in response to local shadow-monitor signals, otherwise free in these directions.

Mass C. The "Secondary Master" mass. Longitudinal, vertical, and horizontal motions damped by moving suspension block in response to local shadow-monitor signals. Longitudinal direction (along beam) otherwise free. Very-low-frequency components (0 to 1 Hz approximately) of vertical and transverse mass position forced to track position of main interferometer beam, by using signals from the beam centering unit for mass C to move the suspension block appropriately. (Precise frequency of crossover from the shadow monitors to the beam centering unit to be determined by their relative signal-to-noise ratios.)

Mass D. A Slave mass. Control of suspension block similar to that of slave mass D, with longitudinal position slaved to mass C by the seismic monitor interferometer. However there is an additional high-precision wide-band control of the longitudinal position of the mass to make the main interferometer arms very closely equal (plus or minus an integral number of half-wavelengths) by direct electrostatic force applied to the mass itself from a capacitor plate on a separately suspended recoil mass, using signals from the main interferometer.

Additional Notes:-

(1) On the frequency stability of the seismic monitor laser source.

The seismic monitor interferometer on the 40-meter prototype uses a normal helium-neon laser stabilized by thermal and piezoelectric feedback to a length of optical fiber. This simple system was chosen for convenience, and could be used in the large system with some additional feedback from one of the arms: as the two arms use the same light source, frequency fluctuations cancel. However in the 4 km design, a by-product from the main interferometer system is a very highly stabilized argon laser source (stable to about a part in 10^{14} in the relevant low frequency region). In this design, a few milliwatts of this laser output is used for the seismic monitor, with its frequency shifted by 40 MHz in an acousto-optic modulator to avoid any danger that scattered light could affect the main interferometer system.

(2) On the low-frequency performance of this isolation system.

The slaved seismic isolation system described above was designed for the Base Model receiver because it is significantly simpler to implement than other active isolation systems of which the author has experience and it is expected to have good low-frequency performance. Realistic prediction of low frequency performance is difficult, since it is likely to be determined by limitations in achievable servo-loop gain set by mechanical resonances in components such as the suspension blocks (which are designed to be as small as possible to keep resonance frequencies high), and by second-order effects. It can be shown that if it were assumed that these latter two phenomena were negligible, and if the monitor interferometer had the same performance as the main one, than seismic noise would not introduce noise equal to the main system shot noise at any frequency above about 10 Hz. These assumptions are far from being realistic, but nevertheless the practical performance is expected to be quite good enough that in this design we consider addition of a more complex system to the Base Model only as Upgrade 2.

(3) Some details.

The present 40-meter prototype uses a single-bounce unequal-arm Michelson for the seismic monitor of a single arm. Higher performance with low light consumption can be achieved with Fabry-Perot cavities in each arm. To keep the size and weight of the mirrors attached to the suspension blocks small, the present design (like the 40-meter prototype) uses lenses in a cats-eye retroreflector system with the lenses supported independently of the suspension blocks, in this case from the isolated baseplates.

(b) Main Interferometer Design - Base Model.

The main interferometer is based largely on the present 40-meter prototype and on experience obtained with this instrument. By designing the Base Model system for operation by a single argon ion laser, giving an input of only about 6 watts, it has been possible to make the design a very conservative one, with no components transmitting unusually high powers, and no requirement for any pockels cell or other electro-optic or acousto-optic modulators any larger than those already used in the prototype. Indeed no components are exceptionally large, and even the main Fabry-Perot mirrors (8 inches in outside diameter, with a 5.5 inches diameter working area) do not require a figure accuracy any better than that of normal good optical components - as will be discussed later. In spite of the low input power and low power rating required of active components, high sensitivity is achieved by a recycling technique.

(1) Laser Source.

The interferometer itself will be described in some detail, but we will just briefly outline the laser system first. The laser light source for the Base Model is in essence entirely conventional - a single commercial argon-ion laser with its frequency stabilized to a highly-stable reference cavity constructed of fused quartz about 40 centimeters long, seismically isolated and suspended in a small vacuum tank. This system will be described later, but key features are use of fast and slow piezo-driven mirrors on the laser to get maximum output and avoid use of radiation-sensitive intracavity pockels cell; wideband correction of residual optical phase fluctuations by an external pockels cell; and use of an auto-alignment system to align the laser beam to the reference cavity. The output beam from the laser source is directed into the "mode cleaning cavity" of the main interferometer system by servo-aligned mirrors, controlled by signals from an autoalignment system monitoring the mode cleaning cavity. This arrangement obviates any need for development of high-power optical fibers, and avoids their possible noise problems and critical adjustment. It can easily handle the power levels of all the proposed upgrades as well as the Base Model system. (A similar active beam pointing system has been extensively used in the 10-meter prototype at Glasgow). The laser source system is designed to permit convenient upgrading in power by adding further similar lasers and combining their outputs coherently. Each additional laser is provided with its own phase locking system, including pockels cell, so the upgrades do not demand any increase in power handling capacity of any sensitive element in the laser source system.

(2) Interferometer.

It may clarify the operation of the interferometer system if we present just simplified schematic diagrams, and in Figures 2A to 2D we show schematic optical systems, and in Figures 3A to 3D an outline of the electronic and control systems associated with each of them. Details such as lenses, amplifiers, etc. are omitted to make the key elements clearer.

In Figure 2A is indicated the basic optics of the main interferometer. Light from the laser source enters from the left, via a radiofrequency phase-modulating pockels cell labelled PC and a polarizing beamsplitter and quarter-wave plate, into a mode cleaning Fabry-Perot cavity C0. The mirrors forming this cavity are coatings on silica masses almost identical to the main test masses, and suspended in vacuum in a similar way. This cavity plays an important role in achieving high sensitivity in the interferometer, for it can define the direction of the primary laser beam with extremely high stability in the gravity-wave frequency range (50 Hz to 5 kHz). Our target here is transverse beam position fluctuations at 4 km distance of order 1 micron over this frequency range. Achievement of this stability is not in any way essential, but it is expected to be fairly easily reached by using suspension and damping techniques for the mode cleaner mirrors similar to those used for the main test masses, and this will make the interferometer relatively insensitive to small-scale surface figure errors and certain scattering phenomena in the main mirrors.

The beam continues via a further phase-modulating pockels cell, polarizing beamsplitter, and Faraday rotator (FR) to the main interferometer. This has in its simplest (PC) form (omitting recycling at this point for clarity) a fused-quartz beamsplitter and compensating plate, two main Fabry-Perot cavities C1 and C2, and a further auxiliary cavity C3 which filters the light reaching the output photodiode D1.

The interferometer has some special features. The beamsplitter is made with a wedge angle of about 5 degrees, and its back surface has an antireflection coating designed to reflect 1% of the light from that surface, to a pockels cell P1, which provides the main internal phase modulation for the interferometer. A mirror M returns light back to the system through the pockels cell. This mirror can be a normal mirror (with autoalignment system and slow servo control of its longitudinal position); but it is also possible to use a wavefront-conjugating "mirror" made from a barium titanate crystal operated as a self-pumped conjugator, and this would very conveniently compensate for optical distortion in the pockels cell as well providing correct alignment and phase of the reflected light automatically. The placing of the main modulator in a side arm of the system in this way has important advantages: it keeps the cell out of the high-power beam, reducing losses and possible radiation damage in a recycling system, and it makes it practical to add a small telescopic lens system (not shown) to reduce the beam size in the pockels cell crystal from the diameter of 2 inches used for the 4 km beams to around 3 millimeters so that the small pockels cell currently used in our prototype interferometers will be large enough. Thus the use of special high-power or large-size components is avoided.

The primary locking system for this basic interferometer is shown in Figure 3A. At this stage two separate frequency-locking conditions are achieved: the cavity C1 is made to resonate with the light from the laser and the cavities C2 and C1 are brought into precise resonance with one another. The locking technique used here (and in many other places in the system) is our now-standard radiofrequency reflection locking method[*1*]. Frequency modulation at 12 MHz by the pockels cell P1 is used for both functions. The locking into resonance of cavity C1 is done by coherently demodulating the signal from auxiliary photodiode D2 and using this to move appropriately the suspension point of the end test mass of this cavity by a coil-magnet system. (At this point the laser light is already well stabilized by the DC-stable reference cavity, assisted at high frequencies by some feedback from the high-frequency-stable mode cleaner cavity, so a narrow bandwidth low-power feedback loop is adequate.) The main locking of cavities C1 and C2 together is done with much wider bandwidth and precision, using the full light power in the system, with diode D1[*].

This outline covers in a basic way the primary locking of the main interferometer, but in the actual full system some further locking or stabilizing conditions have to be achieved. In particular it is necessary to ensure that the distance between the input mirrors on the cavities C1 and C2 and the beamsplitter are kept such that a maximally dark fringe is obtained at photodiode D1 when both these cavities are in resonance, and also that the auxiliary cavities C0 and C3 are kept in resonance. We will now briefly outline the key aspects of the actual system proposed to achieve this, referring to Figure 2B, which shows the optics more completely and Figure 3B for overall locking system. (Several aspects of the technique proposed have not been described before). Arrangements for light recycling are shown in these figures, and use a recycling mirror assembly R.

The method we propose here to achieve the locking conditions for the main interferometer uses two distinct locking systems operating over effectively identical beam paths, but with light sufficiently different in wavelength (by about a part in 10^6) to be clearly distinguishable, in a simple

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*•1 Drever, R.W.P., Hall, J.L., Kowalski, F.V., Hough, J., Ford, G.M., Munley, A.J., and Ward, H., *Appl. Phys.* B 31, 97-105 (1983)

*No control of mirror M is shown in Figure 3A, since it is not required if a wavefront conjugating mirror is used. If, however, a normal mirror is used, an autoalignment system similar to those described later for control of other mirrors in the system would be incorporated, and in addition a servo system would be used to control the longitudinal position of the mirror to give correct mean phase for the reflected light. (The servo system envisaged here would be a narrow-bandwidth one, using low-frequency small-amplitude dithering of the mirror position to optimize the 12 MHz modulation amplitude, in a way similar to that indicated later in Figure 4C for optimizing the coherent addition of the outputs of two lasers.)

automatic way, by the system; and to give a clean discrimination between light reflected from the input cavity mirrors and from within the cavities C1 and C2 themselves. The main interferometer uses light with the wavelength of the light input at the first pockels cell P2, and in effective resonance with the cavities C1 and C2 in the recycling conditions. A secondary interferometer uses light different in frequency from the frequency of the primary light by a frequency F1, which we label as nominally 500 MHz. This secondary wavelength is generated as a sideband of the primary input beam by phase modulation at 500 MHz. It may be described as an optical sub-carrier, and an auxiliary optical cavity C4 is arranged to adjust itself to resonate with this component of the light, and select this light for transmission to auxiliary photodiode D3. The cavity C3 previously mentioned is arranged to perform the opposite filtering function, and prevent this secondary light reaching the primary diode D1. The primary light comes mostly from resonance within the two cavities C1 and C2, while the subcarrier is arranged to be totally out of resonance with them, and thus is effectively just reflected by the input mirrors. Thus the two components of the light separately measure the two required quantities, and are quite independently detected by the two photodiodes. With appropriate feedback forces applied to the mass D and the beamsplitter, the required conditions for optimum operation of the whole interferometer are achieved.

This outlines the principle of the new technique proposed, but to make the system convenient and practical it is important that the filtering cavities can be made to automatically select their correct light signals and lock to them. To achieve this, a coding signal is applied to the 500 MHz sidebands by phase modulating the 500 MHz modulation signal itself at a frequency F2, labelled nominally 30 MHz. The coherent demodulator for cavity C4 picks out this modulation frequency, and thus locks that cavity to one of the two appropriate subcarriers, so that the diode D3 then observes and locks itself on to the particular 12 MHz sidebands which carry information about the positions of the input mirrors relative to the beamsplitter, and feeds back to set the beamsplitter in the required position. Concurrently, the second coherent demodulator on the output of photodiode D4 picks out the 500 MHz sidebands which identify the primary beam, and locks the filter cavity C3 on to that wavelength. The 12 MHz primary modulation is then transmitted by that cavity to photodiode D1, which then performs the final locking of the main cavities. Thus the system sets itself up entirely automatically, given that the appropriate modulations are provided.

Some small details might be noted here. Both the main measurements are carried out at a frequency of 12 MHz, but the two filter cavities are arranged slightly differently. The primary one, C3, is made to perform the additional task of filtering the main output from scattered radiation or other unwanted light, so it is made with a narrow bandwidth, chosen to roughly match the maximum gravity wave frequency of interest. The free spectral range of this cavity is made to closely match the 12 MHz primary modulation, so that the carrier and the information-carrying sidebands are transmitted by adjacent longitudinal cavity modes. This cavity is thus about 10 meters long for a modulation frequency of 12 MHz, which makes the natural diameter of the resonant mode a good one for strong rejection of light scattered from the walls of the long vacuum pipes. The secondary cavity C4 could be made the same size, but some space can be saved by making this short and of bandwidth large enough to transmit the 12 MHz modulation in the same mode as the 500 MHz subcarrier, as this signal is less critical and can be made more immune to scattering by filtering to a narrow bandwidth.

The description above does not take recycling into account, but this is a relatively straightforward addition. A special mirror assembly, labelled R (described in note 3 below), is used for recycling. Pockels cell P2 is used to apply an additional 14 MHz phase modulation to the main beam, which is then picked out by the photodiode D5 and used to lock the recycling mirror in the position for optimum operation. To avoid any loss in amplitude of the 500 MHz subcarrier in the recycling mode the free spectral range of the internal cavity formed between the recycling mirror and the input mirrors for cavities C1 and C2 is made to be a multiple of the 500 MHz modulation frequency, so that there is buildup of the subcarrier as well as of the primary beam.

Notes:-

1. The input mode cleaning cavity is locked by photodiode D6.

2. Mirror Figure Accuracy. A technique is proposed for much reducing demands on the figure accuracy of the super-polished mirrors which had earlier been thought necessary for good recycling. We propose the mirrors are made with only normal accuracy (of order one tenth wave). Then the compensator plate is manually hand figured while set up in an interferometer test rig using the actual components made for the real system, so that the hand-figured plate can correct for the sum of the errors in all the other parts. This is significantly easier since the compensating plate has no need for super polish, and only one surface has to be worked on for the whole system. It may be noted also that as the compensating plate operates in transmission rather than as a mirror defining the wavefront of a nearly-Gaussian beam the effect on the optical path of a given dimensional error is reduced by a factor of approximately $\mu/(\mu-1)$ for normal incidence, which is nearly 3 for fused quartz, and by an even larger factor at Brewster's angle. Thus the compensating plate has much less critical demands on figure accuracy than the surfaces of the cavity mirrors. The whole approach looks a very practical one. We have been told by Perkin Elmer that the required accuracy is normal practice with hand figuring, and over larger areas than ours.

3. Acquisition of recycling condition is aided by use of a variable reflectivity mirror for R. One way of doing this is to have two close mirrors, separated by piezo transducers, so that the small cavity between them can be easily brought into resonance or out of resonance, thus changing transmission of the pair, and altering effective reflectivity. (Other ways of achieving this aim are possible, including use of frustrated internal reflection, tested earlier at Caltech, or a commercial variable polarization beamsplitting unit.)

4. Figures 2C and 3C show the essence of the beam centering and automatic alignment system for the whole interferometer. The unit marked AA is an automatic alignment system which matches wavefront phase, similar to the original prototype unit at Caltech. The action of this unit is effectively an extension of our old laser phase-locking technique to the spatial domain, and it uses the same basic radio-frequency techniques, mostly here with the same 12 MHz modulation frequency as the cavity and laser locking systems. Like the phase-locking technique, it uses light efficiently, has good signal to noise ratio, and can have wide bandwidth - up to about 1 MHz.

The unit marked BC is a device which tracks test masses or cavity mirrors and monitors deviation of the main beam from the center of the relevant mirror. It uses quadrant photodiodes both for the measurement and for locking itself to the mirror of interest. Arrows indicate rotational or displacement corrections applied by these units.

To follow the operation of the complete centering/aligning system it should be realized that the AA units can be made either to lock a laser beam along the correct common optic axis of a pair of fixed cavity mirrors (even though this axis may not pass through the center of either mirror), or to lock a pair of cavity mirrors into correct orientation with a fixed laser beam - in each case with wide bandwidth. In the design here we then can arrange that a pair of BC units can monitor the beam relative to the centers of the mirrors, and can then (more slowly) cause the locked beam to move to the centers of the mirrors, or alternatively can cause the mirrors to center themselves around the locked beam. Both applications are used here.

In the complete interferometer design, the master mass A and the slave mass B define the main optical alignment of the whole system. BC units 1 and 2 lock the beam to the centers of the masses by applying suitable transverse motions to the mode-cleaner mirrors which control the direction of the input beam to the system. AA unit 1 sets the orientation of the masses accordingly. Thus these two nearly inertial test masses determine - via the mode-cleaner - the alignment and transverse location of the whole beam, running right from the left hand edge of the Figure. In the second arm of the interferometer, one end of the input beam is forced to meet the now-fixed primary beam (at the beamsplitter), and the other end of the beam is defined by the BC unit 3 monitoring the mirror on test mass D, and applying suitable rotation to the beamsplitter. BC unit 4 then causes test mass C to center itself to the now-defined beam, in vertical and transverse directions. (This is at low frequencies only - high frequency control of mass C comes from the shadow monitors.) AA unit 2 keeps the masses C and D aligned correctly to the laser beam throughout.

Similar actions are repeated throughout the system. The recycling mirror is centered to the beam by BC unit 5, and aligned by AA unit 3. The mode cleaner mirrors are kept aligned by AA unit 4.

The laser light source itself is controlled in the same way (although not shown in Figure 3C). An AA and pair of BC units lock the laser beam to its own high-stability reference cavity, and the laser beam passes via two servo- controlled beam steering mirrors to the mode cleaner in Figure 3C. These two steering mirrors get their control signals from the BC units 6 and 7, so that the beam is forced to lock itself down the center of the mode cleaner. This part of the system performs several of the functions previously done by optical fiber in prototypes, in allowing some independence and even relative motion between the positions of the laser system and the interferometer, and providing some (slow) beam-dewiggling action. However this system proposed here ensures that correct alignment is maintained entirely automatically, and it can handle much higher powers than a fiber system with presently-available fibers.

Finally, the filtering cavities for the output photodiodes are aligned by their own AA units, with a pair of BC units for the larger cavity. (A BC unit is not shown for the small cavity, as this is a small rigid Tropel or similar cavity and less critical, but BC units could be used here too if needed.)

It may be noted that a system of the type proposed here should be much more user-friendly than any of the prototype gravity-wave interferometers, and capable of both reaching much more precise alignment than a manual system, and maintaining it for long periods. A manual alignment system is still required for initial start up, and in this design we propose use of a computer-controlled switching system to keep the manual system monitoring and adjusting its own alignment during normal automatic operation, but giving switch over to the manual system in event of loss of lock or other automatic-system failure. On recovery of lock, the system would switch itself back to automatic operation, giving minimum disturbance. This system will be very similar to the one currently being set up for initial tests on the 40-meter prototype with an IBM PC as a simple control computer.

It is felt that an automatic alignment system is an essential feature for a 4 km interferometer, and the Fabry-Perot cavity autoalignment device already demonstrated on one arm of the 40-meter prototype provides a very precise and drift-free way of achieving this, as indicated in this design. The system may appear slightly complex overall, but it should be noted that it is made up mainly of many identical copies of just two basic units (the AA and the BC), which will be designed to be suitable for small-scale quantity production.

Further details or explanation of this overall system can be provided if required.

5. Figures 2D and 3D show the downgraded versions of the Base Model interferometer, with no recycling.

6. More precise examples of possible modulation frequencies, and the relations between them, can be provided if requested.

(c) Beam Generating and Control System.

(1) Base Model - Single Laser Source.

The Base Model receiver uses as light source a single argon laser in a two-stage frequency stabilization system, with primary stabilization to a special high-mechanical-Q reference cavity, and a secondary trim for fast frequency fluctuations controlled by the mode cleaning cavity of the interferometer. The arrangement is shown schematically in Figures 4A and 4B.

The laser frequency is controlled by fast, small-range, and slow, large-range, piezodriven mirrors at opposite ends of the laser cavity, aided by a wide-bandwidth trim of output light phase by a series pockels cell. Thus the laser cavity is kept free of electro-optical components which might limit available power or be affected by U.V. radiation damage. The laser beam passes via an isolating Faraday rotator (FR), the phase-trimming pockels cell, an electro-optical amplitude modulator, and a radio-frequency phase modulating pockels cell to the high-Q reference cavity C10. This reference cavity is constructed from a drilled bar of fused quartz, with end mirrors optically contacted to the ends, and is suspended in vacuum by wires from seismically isolated supports using techniques similar to those developed for suspending the bars of room-temperature resonant bar gravity-wave detectors. This gives very low mechanical and thermal noise. An AA unit aligns the laser beam to this quiet cavity by servo-driven mirrors, thus providing a first stage of active beam direction stabilization and beam wiggle reduction. An intensity monitor photodiode D10 controls the amplitude modulator, to stabilize output intensity and act as a "noise eater". The stabilized output beam then passes via a second phase-trimming pockels cell (at the right-hand side of Figure 4C, labelled PC) and a second pair of direction-controlling and position- controlling servo mirrors to the mode-cleaning cavity C0 of the main interferometer. This second phase-trimming pockels cell receives control signals covering frequencies from about 20 Hz upwards from the mode-cleaning cavity, to give a second wide-band high-gain frequency stabilization loop based on the even quieter high-frequency reference given by the heavy isolated masses and mirrors of the mode cleaner. The overall system is shown in Figure 4B. The complete two-stage frequency and direction stabilization system is designed to give a final beam suitable for the main interferometer without requiring any frequency control from the 4-kilometer arms, thus avoiding any possible complications from kilometer propagation delays or the small free spectral range of the 4-kilometer cavities.

It may be noted here that in these and subsequent diagrams each set of servo-driven mirrors used for controlling beam direction and position are indicated as a pair of mirrors. In fact separate fast small-range mirrors and slower wide-range mirrors are employed, to give a good combination of dynamic range and speed of response, and using four mirrors per set (an arrangement which has long been used in the Fabry-Perot prototype at Glasgow). Further stabilization of beam direction and position extending to the highest frequencies is provided passively by the mode cleaner C10. The dimensions of the mode cleaner cavity are determined in part by possible thermal effects in the mirrors at high power densities, and as well as by considerations of directional stability. For the power level of the Base Model receiver a cavity 0.5 meter long could be adequate, but for the higher power levels of the proposed receiver Upgrades a cavity of length a few meters is envisaged and as this will also give better directional stability this size is chosen for the Base Model design.

It should be emphasised here that the schematic diagrams given show only one of a large number of possible design variants, and are intended to illustrate more the general approach than the final details. In this laser stabilization system, for example, it may prove useful to supplement the Pockels cell phase shifter shown in the first loop by an acousto-optic frequency shifter; or it may be useful to feed back a trimming signal from the second stage stabilizing loop to the first one. Current work with prototype interferometers is giving practical experience of these and other variants of the basic stabilization system. The arrangement shown in the figures is a fairly straightforward one, and a reasonable choice for the present design.

(2) Upgrade 1 - Coherently-Added Multiple Laser Source.

To upgrade the receiver it is proposed that light power be increased by adding coherently the outputs from several lasers, and use of four lasers is illustrated here as Upgrade 1. Figures 4C and 4D indicate schematically how this is done. The light frequency is determined by a single primary laser, and additional "booster" lasers are phase locked to the output of the primary laser and added coherently to it.

The primary laser system is identical to the Base Model laser system described above, and this defines the initial frequency and directional charecteristics of the output beam. Each booster laser has its frequency, phase, and beam direction slaved to that of the primary laser, as is shown for one secondary laser in Figure 4C. The beam from this laser, after intensity and directional stabilization, passes to a beam combining assembly incorporating two polarizing beamsplitters (labelled PBS) and a half-wave plate, which add it coherently to the beam from the primary laser, and also provide the necessary phase and direction information. The action of this beam combining aassembly can be considered as equivalent to that of a single beamsplitter of variable reflectivity. The output beams from both the primary and secondary laser are plane polarized, but it is arranged that their planes of polarization are in orthogonal directions, such that the beam from the primary laser is transmitted by the first polarizing beamsplitter, and that from the secondary laser is reflected, so that the two beams emerge in the same direction with orthogonal polarizations. If they are phase-locked together correctly, the resultant will be a single beam with polarization plane at an azimuthal angle determined by the relative amplitudes in the two components. The half-wave plate following the first beamsplitter can rotate this plane of polarization to any required azimuthal angle, and it is adjusted to make the resultant beam optimally transmitted by the second polarizing beamsplitter. In fact the radiofrequency phase modulation of the beam from the secondary laser will lead to some sideband light having a polarization component orthogonal to that of the main combined output beam from the second beamsplitter, and this will be reflected to the side by that beamsplitter. This rejected light passes to a photodetector (and an AA unit), and carries the information on the phase difference between the input beams from the primary and secondary laser which, when coherently demodulated, provides a locking signal for the secondary laser. This laser thus locks itself to the primary laser beam, and its output reinforces it. The autoalignment unit also generates mirror control signals which align the beam from the secondary laser to that from the primary one, so that efficient combining of the two beams is achieved.

The optimum azimuthal orientation of the optic axes of the halfwave plate relative to the axes of the polarizing beamsplitters is a function of the ratio of the intensities of the beams from the two lasers, and it could be adjusted manually if desired. However we illustrate an automatic adjustment system in Figures 4C and 4D, which can cope with changing laser output powers if necessary. The halfwave plate is mounted so that it can be rotated about the beam by a servo system, and also modulated in azimuthal angle by a few degrees at a low frequency, indicated here as 10 Hz. The 10 Hz dither modulates the mean intensity of the light rejected by the second beamsplitter and reflected to the side, and a lock-in detection system referenced to the 10 Hz modulation can then provide a signal which rotates the halfwave plate to the position giving minimum reflected light, and maximum output in the combined beam. The whole system thus adjusts itself for varying laser outputs, and always provides the maximum output power which could be obtained.

The complete system, with one primary laser and three secondary ones, is shown in Figure 4D. The secondary laser systems use different modulation frequencies to avoid possible interaction, but are otherwise identical.

It may be noted that reliable coherent addition of a number of argon lasers requires that the single mode etalons used in each laser to select the operating longitudinal mode must be adjusted to select modes close in frequency to one another - at least to within about one free spectral range. Commercial lasers are designed so that the etalon is sufficiently stable for initial manual adjustment to be adequate, and this may be adequate for this system also. However an auxiliary control system for optimizing the adjustment of the resonant frequency of the single mode etalon in each laser could improve the reliability of long-term operation, and we propose such an Etalon Frequency Control (EFC) system in this design. The device proposed slowly dithers the etalon frequency through a small range, and by a lock-in system operating on the output from the internal laser power monitor, along with other laser data, gradually moves the etalon resonant frequency to the setting giving maximum laser efficiency. Such a feedback etalon control system could also improve long-term performance of the single laser of the Base Model Receiver. More details can be provided if necessary.

The multiple laser source system outlined here can be extended to larger numbers of argon lasers. At a certain point it will probably become economical to switch to a more efficient type of laser system, such as a NdYAG laser with frequency doubler. For high power levels the system can consist of a low power laser oscillator followed by a laser amplifier and a frequency doubler, and in this case a stabilisation system similar in principle to that for the Base Model may be suitable for controlling the oscillator stage. The wavelength of the light from a doubled NdYAG system (530 nm) is sufficiently close to the wavelength of the green line from the argon lasers used in the design here (514 nm) that this switch of laser type can be made with minimal changes to the rest of the receiver system, when suitable stabilized frequency doubled NdYAG laser systems become available. In this design this switch is suggested as Upgrade 3. The basic design outlined here seems capable of extension to much higher power levels than proposed for initial use, with corresponding long-term advances in ultimate performance.

Further Notes:-

1. I have not had time to show how this type of receiver is mounted into the vacuum tank concept with vertically removable masses outlined earlier - but it is designed to do this, and give a relatively small shadow cross-section. The upgrade with full active seismic isolation is illustrated in rough outline in Figure 5, and differs from the Base Model only in that each shadow sensor monitor is replaced by an active antiseismic guard system, with reference arm for horizontal motions. As before, the mass of the suspension block to which the feedback is applied is kept as small as possible, so good frequency response and correspondingly high loop gain is practicable. With this system it is expected that thermal noise in the suspension may be the main limiting factor in extreme low frequency performance, but it should be noted that early work at Glasgow has given pendulum relaxation times of more than about 0.2 years for a half-second simple pendulum, with two different designs of suspension flexures (a machined and etched aluminum ribbon assembly, and a fused quartz fiber suspension with the fiber drawn to minimum diameter at the flexure point while mounted in place and supporting the test mass). Also V.B. Braginsky[*2] has reported a pendulum with 1 year relaxation time. It is intended in the design here that thermal noise at high frequencies will be made to match that corresponding to relaxation times of at least this order, so that even the relatively small test masses proposed for the Base Model interferometer are expected to give good low frequency performance.

2. Please don't hesitate to ask me about anything in the whole system that is not clear. I apologize for the rushed nature of this account. I am sorry I have not had time to describe more of the details, but although the concepts have been developing over a long period of time I have not written most of them down before.

Ron Drever

[*2] Braginsky, V.B., Polnarev, A.G., Thorne, K.S., *Phys. Rev. Lett.* 53, 863-866 (1984).

FIG. 1. BASE MODEL TEST MASS ARRANGEMENT

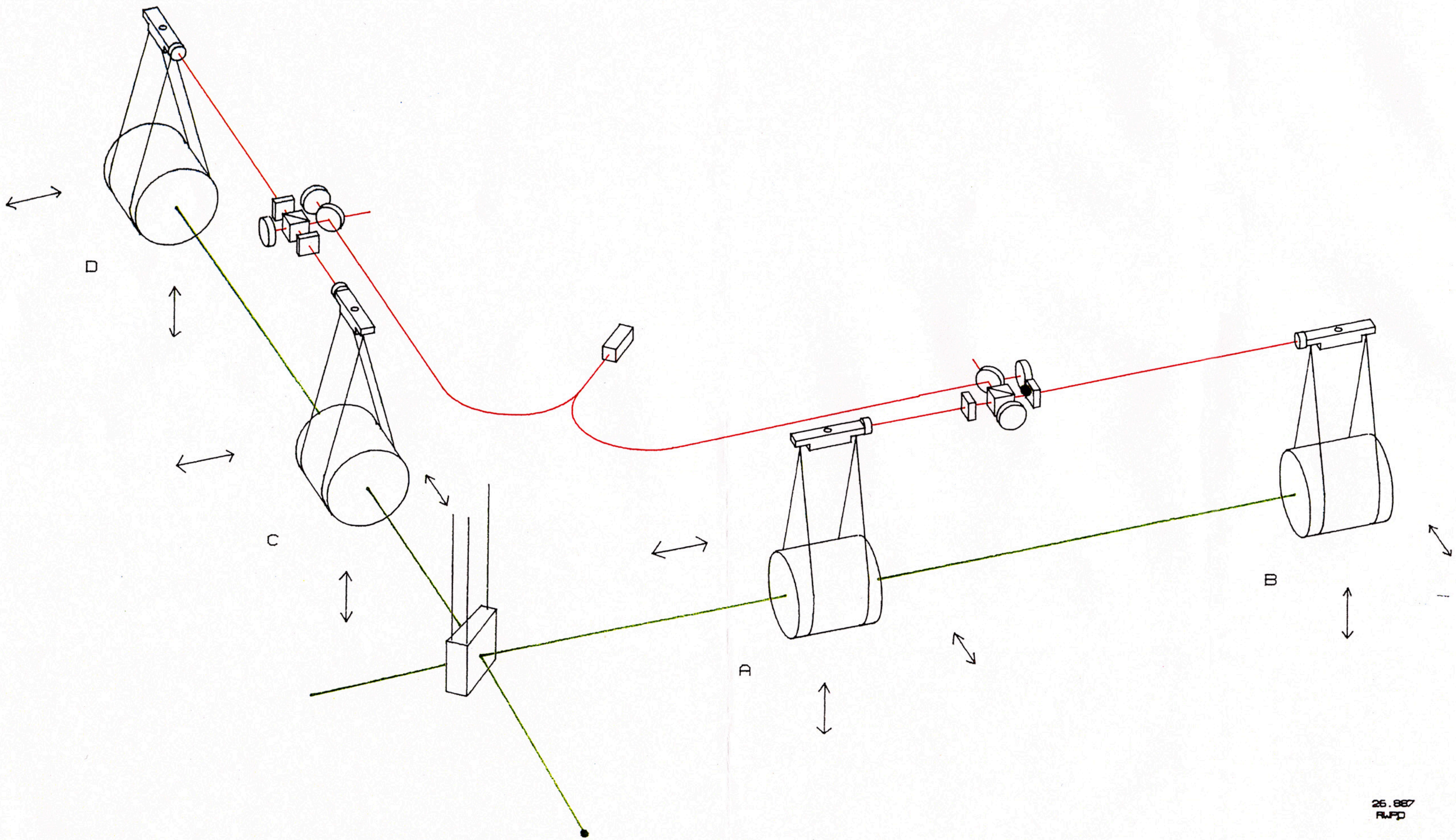
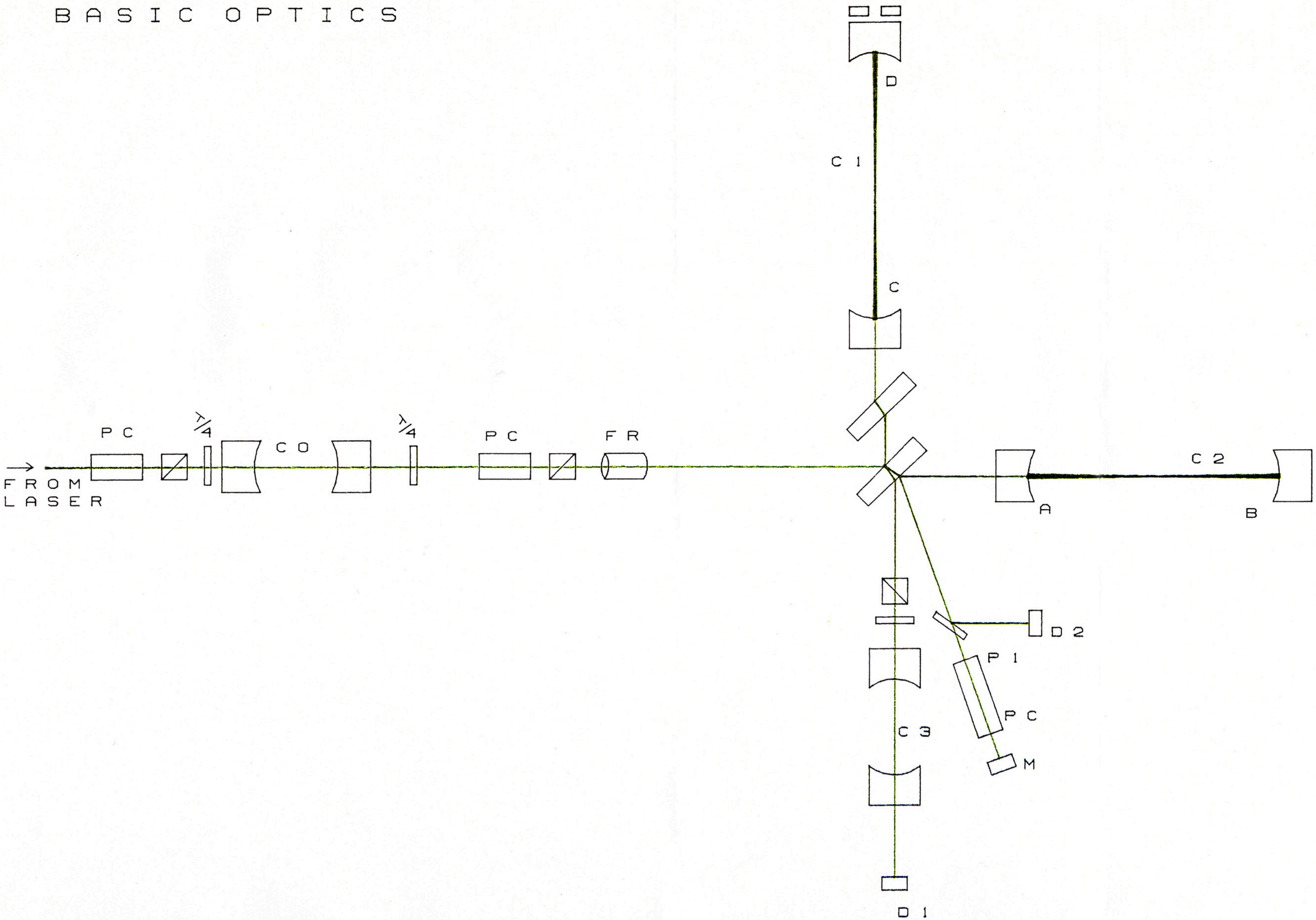


FIG. 2A

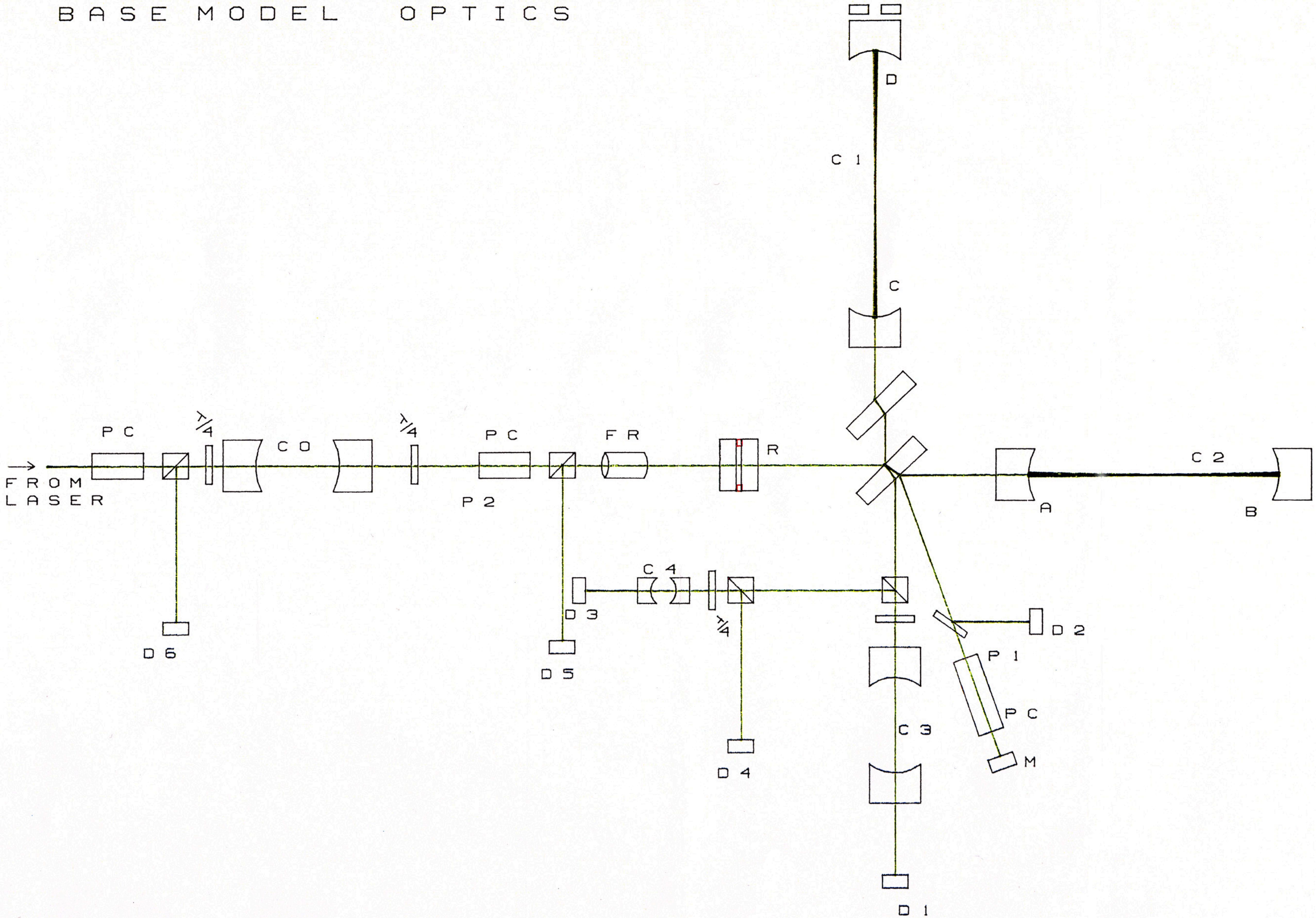
BASIC OPTICS



26.867
RWPD

FIG. 2B

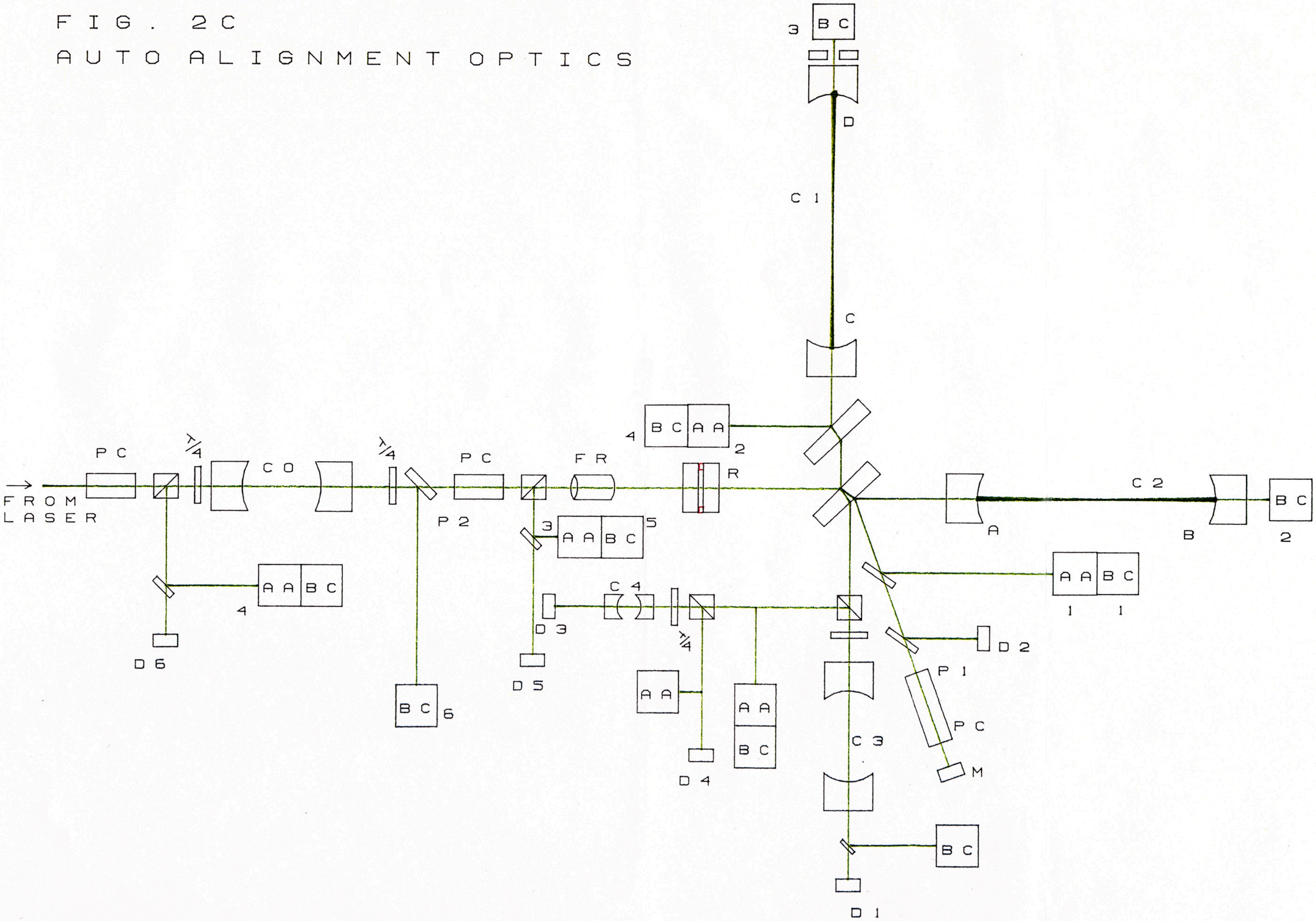
BASE MODEL OPTICS



26.887
RWPD

FIG. 2C

AUTO ALIGNMENT OPTICS



26.887
RWPD

FIG. 2D

DOWNGRADE 1

NONRECYCLING OPTICS

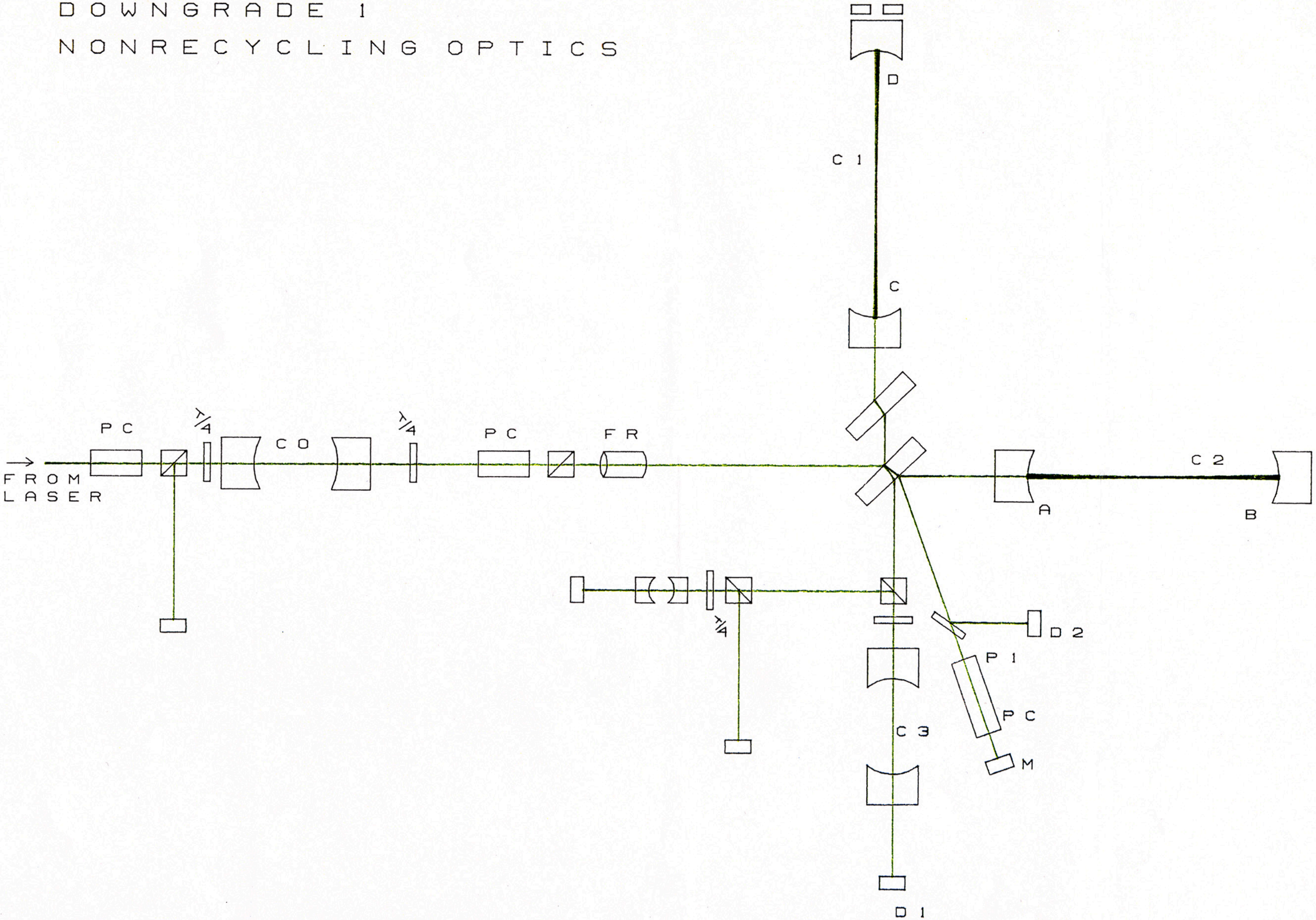
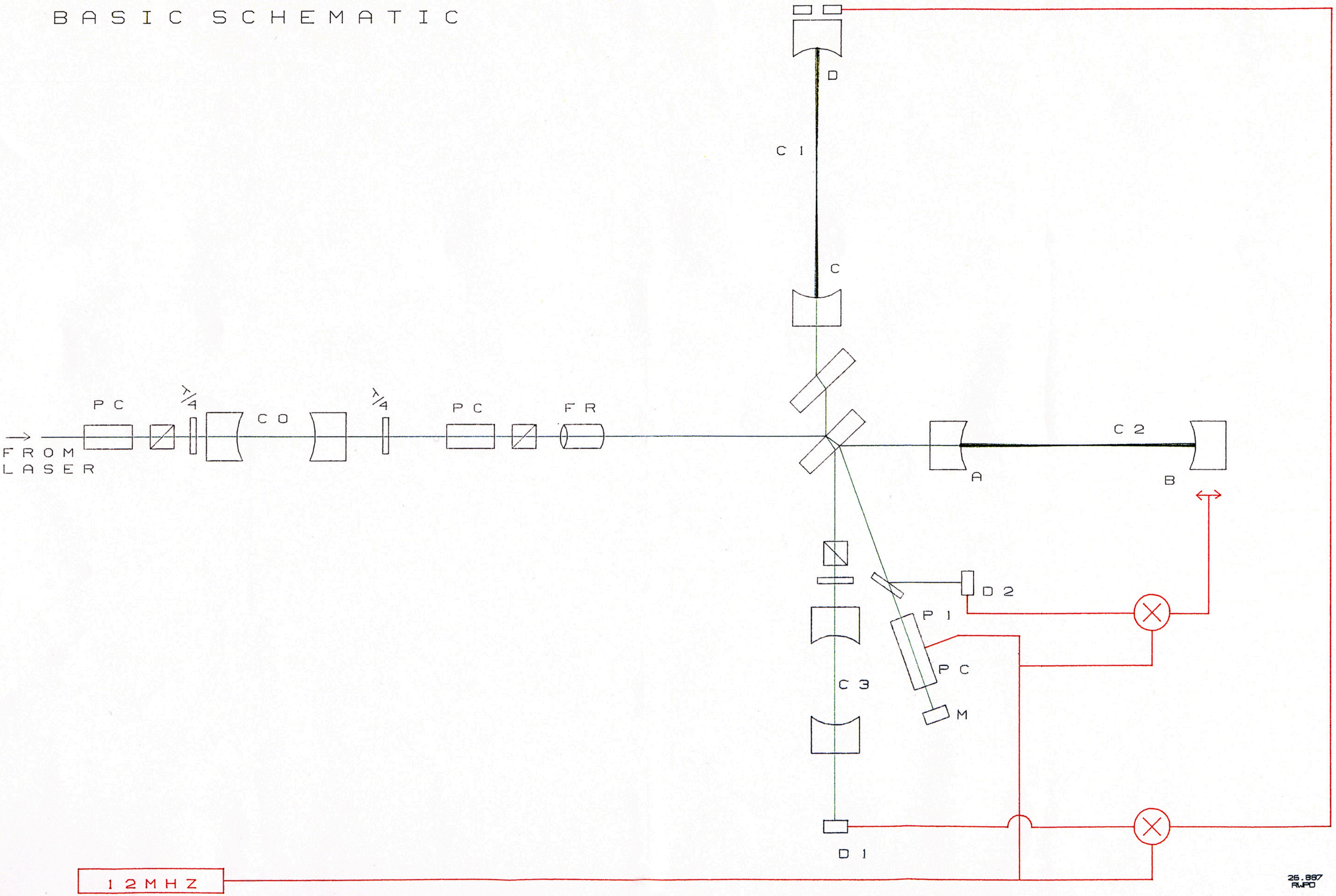


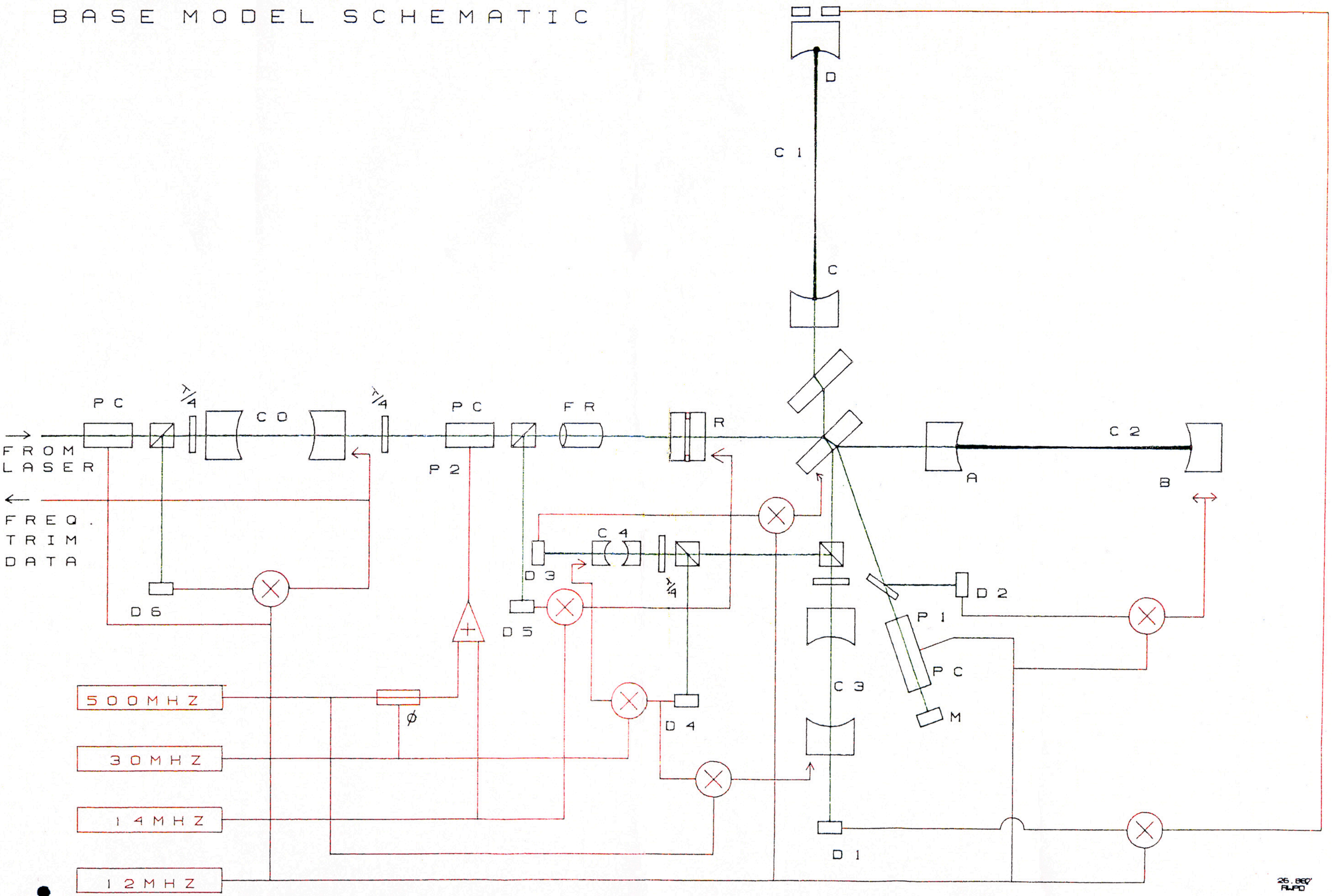
FIG. 3A
BASIC SCHEMATIC



26.887
RWPD

FIG. 3B

BASE MODEL SCHEMATIC



26.887
RWPD

FIG. 3C

AUTO ALIGNMENT SCHEMATIC

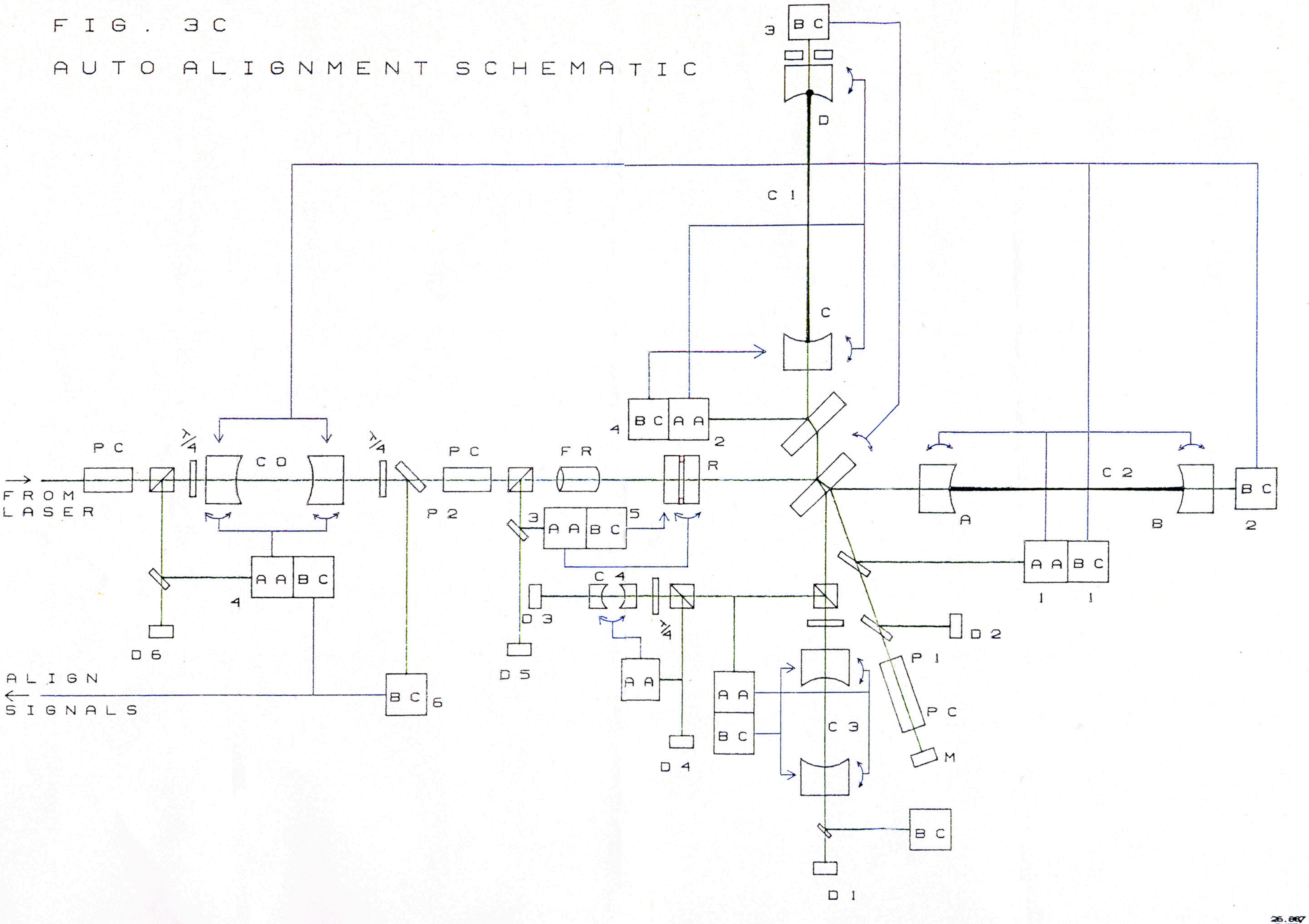
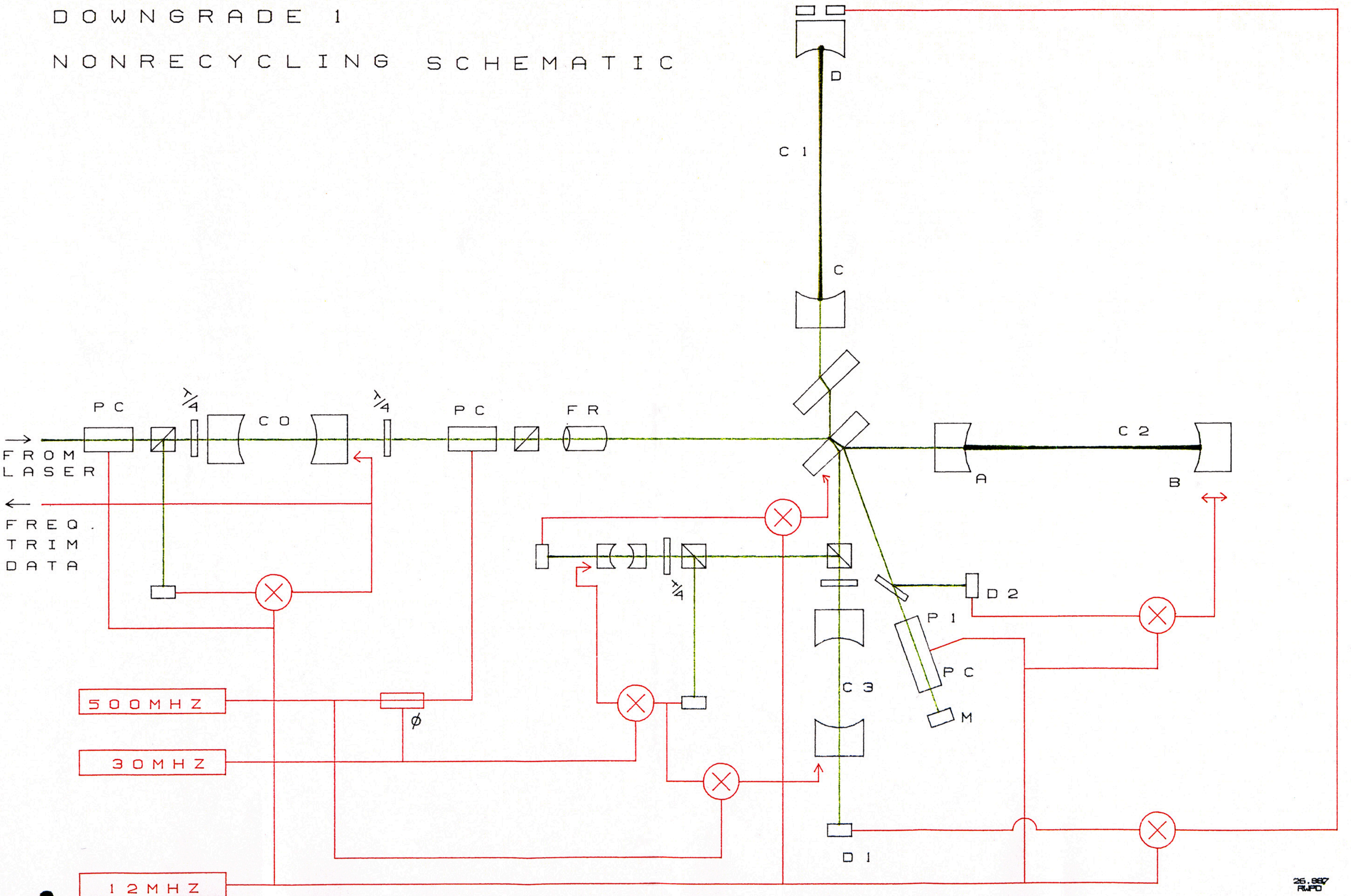


FIG. 3D

DOWNGRADE 1

NONRECYCLING SCHEMATIC

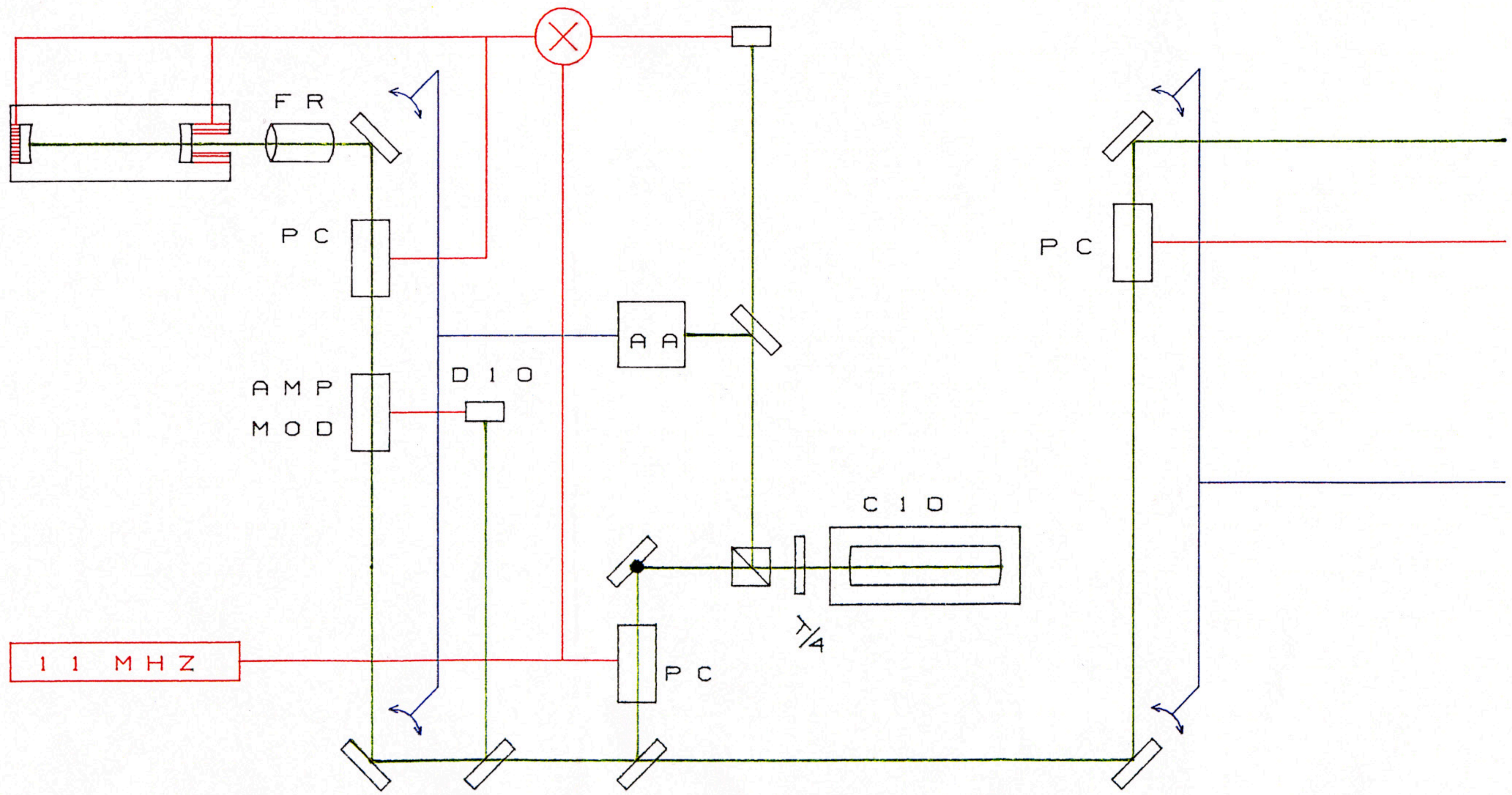


26.887
RWPD

525 3D

FIG. 4A

BASE MODEL LASER SYSTEM



SCZ 4A

FIG. 4B

COMPLETE BASE MODEL

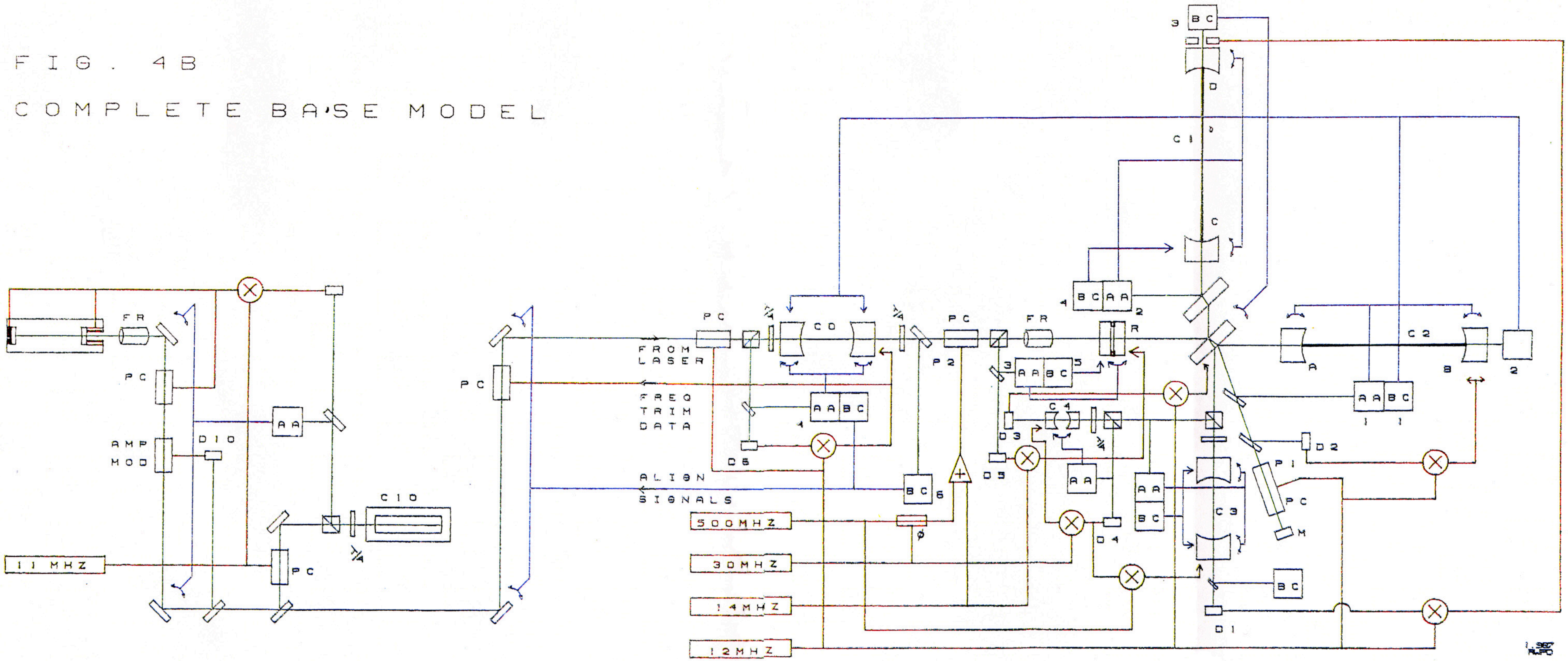
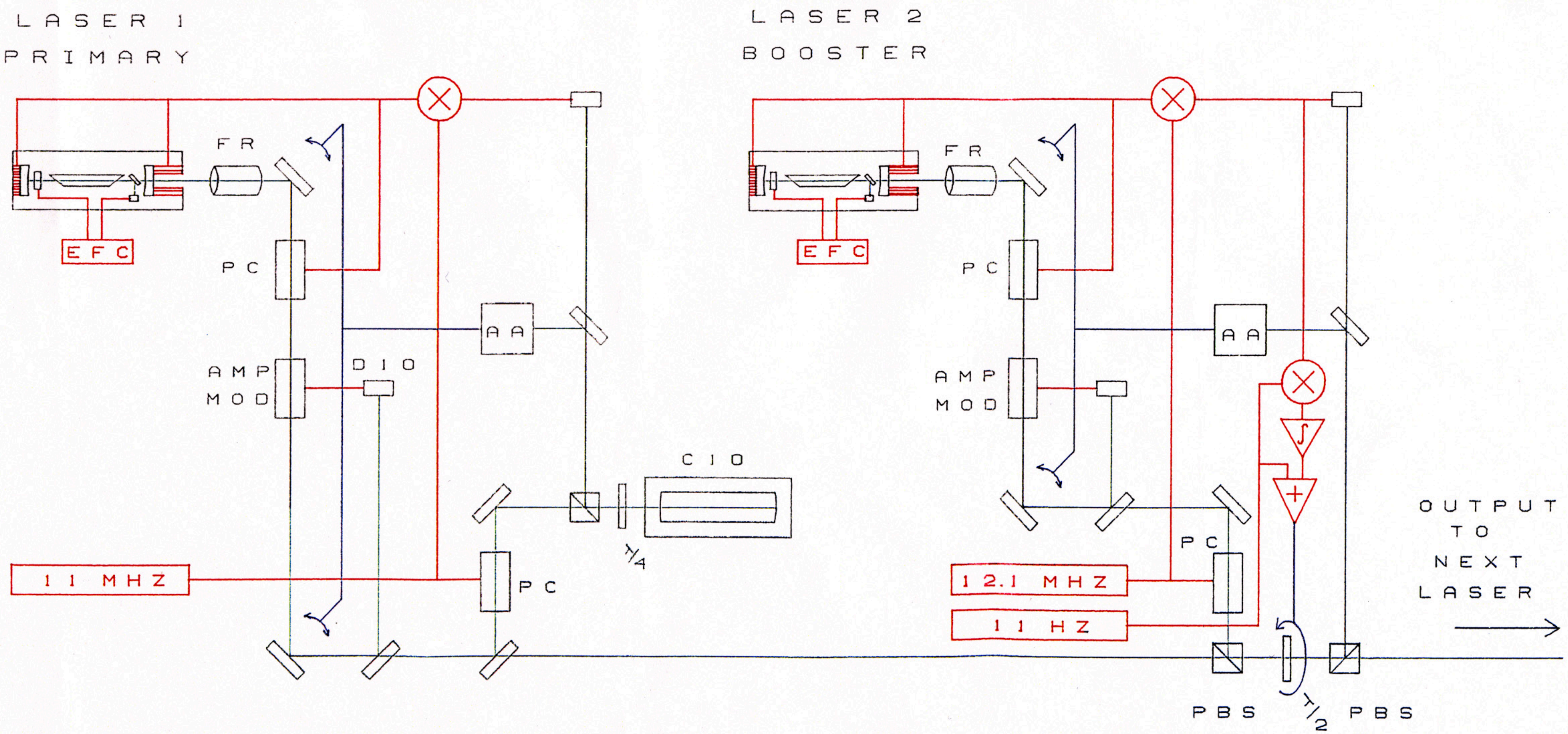


FIG. 4C

LASER UPGRADE 1

SHOWING 2 OF THE 4 LASERS

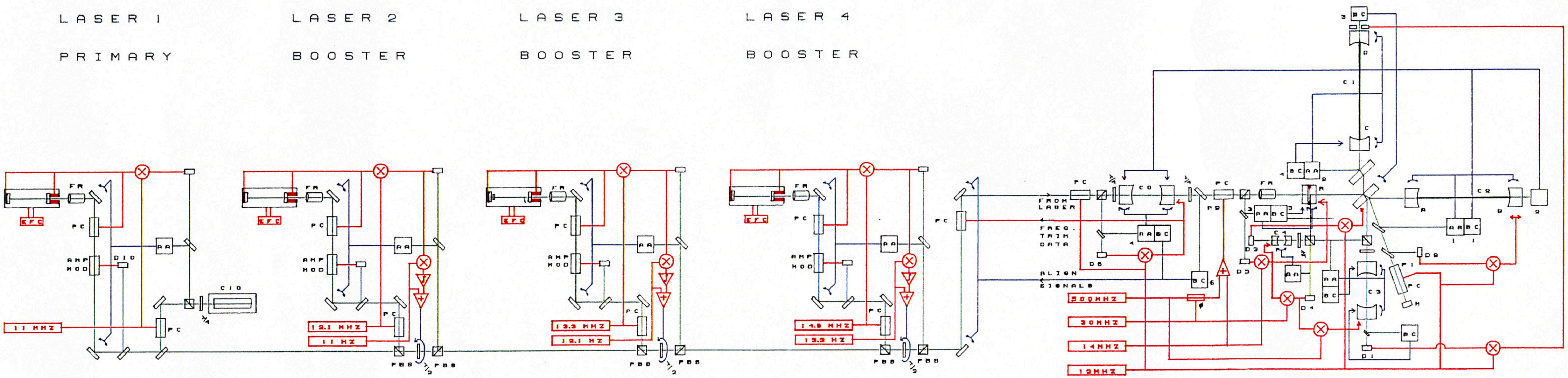


13.987
RWPD

FIG. 4D

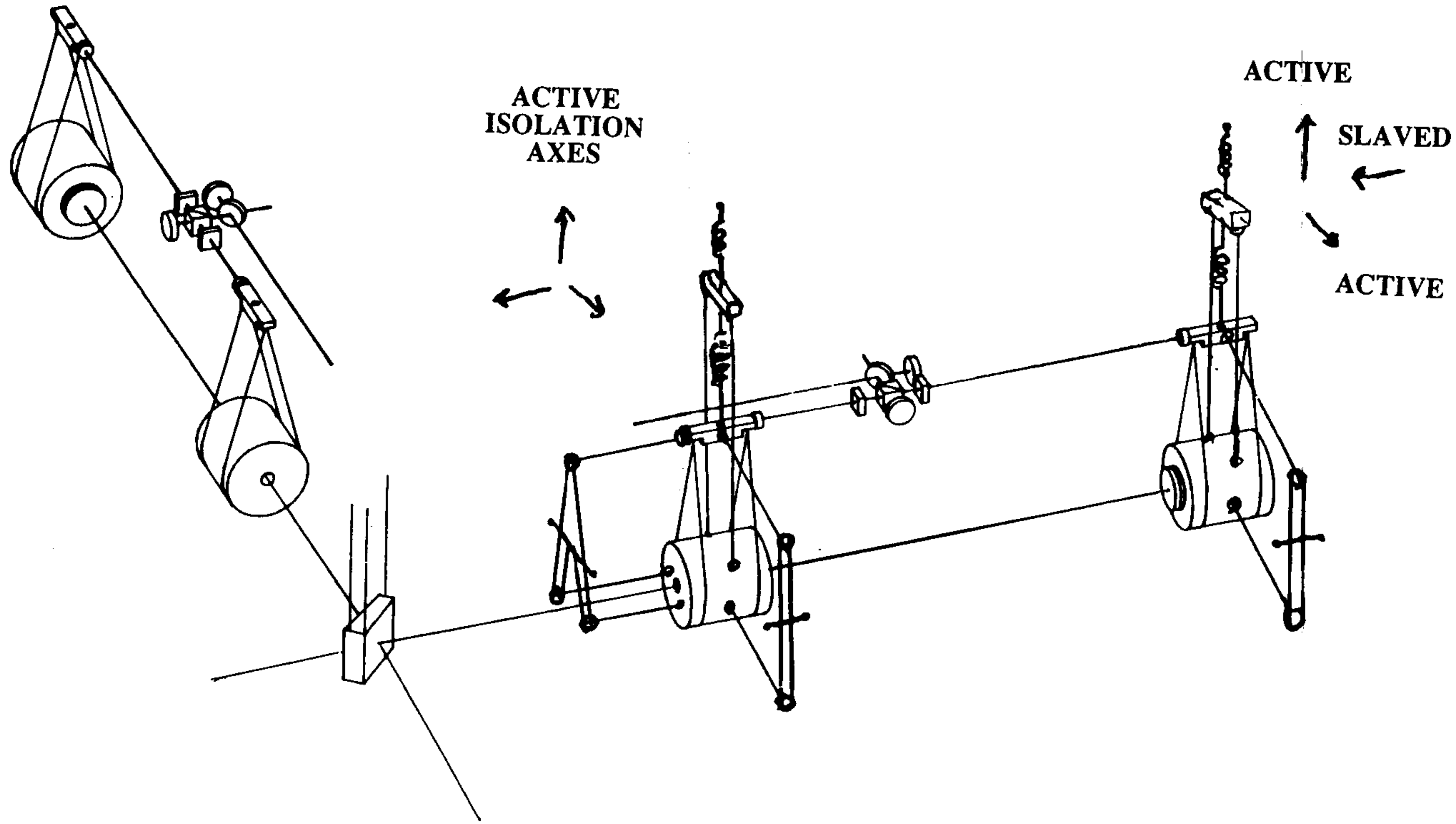
UPGRADE 1 SYSTEM

WITH 4 LASERS



13,987A
RWPD

FIGURE 5. Upgrade 2 - Use of an active antiseismic guard system to supplement the slaved seismic isolation system of the Base Model.



Note: This sketch only illustrates the principle, and the way the various degrees of freedom are controlled in one arm by a combination of the slave and the guard systems. The other arm is arranged in the same way, but is not drawn in here, for simplicity.

48A
RWPD