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A PROPOSED METHOD OF MEASURING SYNCHROTRON-RADIATION PULSES IN THE PICOSECOND RANGE

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ABSTRACT

In electron or positron synchrotrons and storage rings working at 500 Mhz, the electron or positron bunches get extremely short (approximately 50 to 150 psec), so that conventional methods of measuring the bunch-structure are impossible. In this paper a method is discussed for measuring the structure of the bunches by means of synchrotron radiation with a recently developed laser technique.

INTRODUCTION

For the projected DESY storage ring an acceleration frequency of 499.67 MHz will be installed to obtain a high luminosity [1]. The bunches have lengths between 50 and 150 psec. In the curved sections electrons and positrons emit electromagnetic radiation (so-called synchrotron radiation). The intensity of synchrotron radiation depends both on current and energy [2]. Since the synchrotron radiation has the same structure as the current distribution in the accelerator, it is possible to measure the bunch-structure by determining the intensity structure of the emitted synchrotron light.

POSSIBLE METHODS OF MEASURING SHORT LIGHT PULSES

Since 100 psec is the upper limit of the rise time of conventional photodetectors (photodiodes and photomultipliers), a photodetector gives the same response to a pulse of 1 psec as e.g. to 50 psec pulselength. Therefore an assertion of the structure of a pulse shorter than approximately 1 nsec is impossible. In the last three years a laser technique was developed which made it possible to obtain light pulses with pulse lengths of a few picoseconds and pulse powers of several hundred megawatts. With this technique it may be possible to measure the synchrotron light-pulses with optical sampling methods. This method is discussed in the following sections.

MODE LOCKING OF LASERS

A laser consists of the following elements: a rod with laser-active material, a pump equipment and two mirrors (fig.1). One of the two

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[1] Vorschlag zum Bau eines 3GeV Elektron-Positron-Doppelspeicherrings für das Deutsche Elektronen- Synchrotron DESY, Hamburg, September 1967, p.70

[2] J.Schwinger: Phys. Rev. 75, (1949), 1912

mirrors has a reflectivity of 100%, the second a reflectivity of about 90%. In thermal equilibrium the electrons of the laser medium populate the low-energy levels (fig.2). When the laser-rod is pumped by flashlight the electrons populating level 1 absorb photons and rise to level 2. From level 2 electrons can reach level 3 (laser level) without emitting electromagnetic radiation. The life time of the laser level is extremely large (typical value: 10^{-6} sec). When an electron falls from the laser level to the original level 1, it emits radiation (random process). The emitted photon is able to cause stimulated emission by another inverted electron. The process of stimulated emission can be described in the following manner: when a photon emitted from the laser level travels through the laser rod, it can be absorbed by a noninverted eletron (fig.3a). When a photon reaches an inverted electron, it can interact with the electron in such manner, that the electron falls to level 1. The electron emits a photon (fig.3b) in addition to the incoming photon. Two photons emitted by uncorrelated processes have a random phase difference, two photons emitted by stimulated emission have always the same phase: the light beam obtained by stimulated emission is coherent.[3] In a laser rod stimulated emission and absorption takes place. When enough electrons are inverted, stimulated emission is larger than absorption and the first, thermaly emitted photon is amplified. The light-beam oscillates between the two mirrors M1 and M2 (fig.1). The mirror with about 90% reflectivity allows to obtain laser-radiation outside the resonator (also called Fabry-Perot-resonator). In the Fabry-Perot-resonator a standing light-wave oscillates. Only such frequencies can oscillate for which the boundary condition is fulfilled:

$$n\lambda = 2L \qquad \ldots\ (1)$$

λ .....wavelength of the oscillating laser-light

n .....integer

L .....optical length of the laser-cavity

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[3] For detailled discussion of the stimulated emission see for instance:
H.G. Unger: Quantenelektronik, Vieweg, Braunschweig, 1967

Since the laser-transition is not exactly monochromatic, several frequencies can oscillate in the cavity, provided that the boundary condition (1) is fulfilled. The selection rules for the possible oscillations in the Fabry-Perot resonator can be derived from (1):

$$n\lambda_1 = 2L$$

$$(n+1)\,\lambda_2 = 2L \qquad (2)$$

$\lambda 1$ ..... wavelength of an oscillating frequency
$\lambda 2$ ..... wavelength of the next oscillating frequency
Therefore the distance between two neighbouring frequencies is:

$$\Delta\nu = \nu_2 - \nu_1 = \frac{c}{2L} \qquad (3)$$

Since the ND-glass laser installed at DESY (fig.4) has an extremely wide-band laser-transition, many modes oscillate in the cavity. [4] Inside the cavity and outside the different modes interfere so that a pulsestructure is obtained (fig.5). Hence the different frequencies oscillate independently, and the phase distribution is random. In order to obtain identical pulse-structures, the modes must be coupled, e.g. by liquids with an intensity dependent absorption coefficient (fig.6). Each frequency passing through that liquid produces harmonics. Only harmonics for which selection rule (1) is valid can oscillate. Therefore a coupling between the different modes take place [5] (mode locking). Considered from the point of view of the time-domain: intense pulses can pass the liquid without loss, small pulses are absorbed and intense pulses are sharpened (fig.7). The pulse repetition frequency can be derived from (1):

$$\nu = \frac{c}{2L} \qquad (4)$$

The pulse repetition rate is defined by the geometrical dimensions of the laser cavity. The pulse width depends both on the band width of the laser-transition and the nonlinear liquid. For a Nd-glass laser the pulse-width is 4-20 psec.

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[4] S.L.Shapiro, M.A.Duguay and L.B.Kreuzer: Picosecond Substructure of Laser Spikes

[5] A.J.deMaria, W.H.Glenn, M.J.Brienza and M.E.Mack: Picosecond Laser Pulses, Proc. IEEE, 57 (1969), 2

MEASUREMENT OF ULTRASHORT LIGHT-PULSES PRODUCED BY MODE-LOCKED Nd-LASERS

Two different methods were developed to measure the pulse-length of light-pulses in the picosecond range: nonlinear fluorescence effects (two photon excitation) and second-harmonic generation.

TWO-PHOTON EXCITATION

The picosecond-pulse train enters a cell filled with fluorescent liquid. The pulse-train is reflected at the end of the cell by a mirror so that the pulses overlap at fixed points of the cell (standing light-wave) (fig.8). Since the fluorescence-time is larger than the duration of the pulse, the liquid works like an integrator. The time-averaged light intensity at each point is constant and an assertion of the pulse-structure is impossible. But when the absorption-coefficient of the liquid is a nonlinear function of photon-intensity, high absorption will take place in the overlapping points, and there will be absorption between these points: the intensity of the fluorescence is modulated by the pulse-structure (fig.9)

The effect of nonlinear absorption was first described by Göppert-Mayer[6] and later again discussed by Kleinman[7]: the two-photon-absorption. The incoming photon has not enough energy to raise the electron to the fluorescence-level (fig.10). For high photon-intensities the following process becomes probable: the electron absorbs two photons and rises to the higher level. The cross-section of that effect is proportional to the square of the intensity. The measuring of ultrashort light-pulses by two-photon-fluorescence was first performed by Giordmaine et al.[8] : in a Rhodamine 6G-cell the pulses of a Nd-glass-laser (1.06 μ) produced an orange fluorescent stripe modulated by the pulse-structure.

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6 M.Göppert-Mayer: Ann.Physik 9, (1931), 273

7 D.A.KLeinmann: Laser and Two-Photon processes, Phys.Rev.125 (1962) , 87

8 J.A.Giordmaine, P.M. Rentzepis,S.L.Shapiro an K.W.Wecht: Two-photon Excitation of fluorescence by Picosecond light pulses
Appl.Phys.Lett 11 (1967), 216

This method has the disadvantage that the cross-section of the two-photon-absorption is very small: only megawatt-peak-power pulses can be measured.

MEASUREMENT OF ULTRASHORT LIGHT PULSES BY OPTICAL SECOND HARMONIC GENERATION

In 1967 Weber proposed a method of measuring picosecond pulses by generation of optical harmonics[9]. Second harmonic generation (SHG) was first performed by Franken et al.[10] and Giordmaine[11]. The authors illuminated a birefringent potassium dihydrogen phosphat (KDP) crystal by intense red laser light and measured the production of ultraviolet light (fig.11). The cross-section of SHG depends on the angle between optical axis and the wave vector of the incident beam. Kleinman[12] and Armstrong et al.[13] developed the theory of SHG: the intense laser radiation represents a high voltage field travelling through the crystal. Since SHG only observed in piezoelectric crystals it is assumed that the nonlinear effect is caused by nonlinear polarization of the medium[14]. The angular dependence of SHG (fig.11) is explained in the following way: two photons (ν_1 , ν_2) with different wave vectors $\vec{k}_1$ and $\vec{k}_2$ produce a photon with energy

$$E_3 = h\,(\nu_1 + \nu_2) \qquad (5)$$

and wave vector $\vec{k}_3$. At another point of the crystal another photon is produced by SHG. When both photons have the same phase, the amplitude of SHG is measurable, for all the produced photons add up to a measurable intensity. When the photons have different phases interference will weaken the SHG-beam. This fact can be expressed by the so called phase-matching-condition:

$$\Delta \vec{k} = \vec{k}_1 + \vec{k}_2 - \vec{k}_3 = 0 \qquad (6)$$

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9 H.P.Weber: Method for Pulsewidth Measurement of ultrashort Light-Pulses generated by Phase-Locked Lasers using nonlinear Optics, J. Appl.Phys. 38 (1967), 2231

10 P.A.Franken, A.E. Hill, C.W.Peters and G.Weinreich: Phys.Rev. Lett. 7 (1961), 118

11 J.A.Giordmaine: Mixing of Light Beams in Crystals, Phys.Rev.Lett. 8 (1962), 19

12 D.A.Kleinmann: Theory of Second Harmonic Generation of Light. Phys. Rev. 128 (1962), 1761

13 J.A.Armstrong, N.Bloembergen, J.Ducuing and P.S.Pershan: Interactions between Light Waves in a Nonlinear Dielectric, Phys.Rev. 127 (1962), 1918.

Weber used a Michelson-type interferometer for measuring short pulses (fig.12). The pulse-train is split into two beams. After passing polarizers the two beams are polarized vertically to each other. Since the phase matching condition (6) is only fulfilled when both beams pass the crystal, SHG with one beam is impossible. When moving one of the mirrors the beam can be delayed. With this method the pulse structure can be measured. Gloge and Roldan [15] demonstrated that even pulses in the milliwatt range can be detected by this method.

OPTICAL SAMPLING METHODS

Duguay and Hansen extended the SHG-method to an optical sampling method [16]. A long pulse (800 psec duration) is mixed in a KDP-crystal with short pulses (4 psec in duration) from a mode-locked Nd-laser. Only when both pulses pass the crystal a second harmonic beam is generated (fig.13). Output intensity is proportional to the product of the intensities of both beams. The sampling pulses are detected by a conventional photo-detector.

PROPERTIES OF THE SYNCHROTRON-RADIATION PULSES

The synchrotron radiation is incoherent and non-monochromatic, but linearly polarized [17]. The power emitted by one electron in the visible range is about $8 \cdot 10^{-10}$ W (nearly independent of energy between 1 and 3 GeV). The synchrotron pulses in the visible range are weak compared with megawatt laser pulses. Therefore a two-photon-measurement is impossible.

Since Gloge and Roldan had demonstrated that even low-power light pulses can be detected by SHG, we first wanted to measure the synchrotron pulses by a combination of SHG- and sampling methods. But there exists one difficulty: the phase-matching condition is only (exactly) fulfilled for one frequency (the sampling frequency is constant). So only a narrow band of the synchrotron radiation can be used for SHG.

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[14] For a detailled discussion of the mathematical treatment of polarization in crystals see, e.g. M.Born and E.Wolf: Principles of Optics, Pergamon Press, New York, 1959

[15] D.Gloge and R.Roldan: Investigation of low power laser signals with picosecond resolution. Appl. Phys. Lett. 14(1969), 3

[16] M.A.Duguay and J.W.Hansen: Optical Sampling of subnanosecond light Pulses. Appl. Phys. Lett. 13 (1968), 178

[17] R.Haensel und C.Kunz: Experimente mit der Synchrotronstrahlung, DESY 67/15, Mai 1967

ULTRAFAST KERR-GATES

With high power light-pulses several optical effects in the picosecond range were studied; among them was the Kerr effect: an electric field induces birefringence in an isotropic liquid and rotates the resulting polarization vector of a light beam (fig.14). Mayer and Gires[18] demonstrated in 1964 that the electric field of a light beam can induce birefringence. Duguay and Hansen [19] studied the Kerr effect in the picosecond range. They used an intense mode-locked Nd-laser beam (fig.15). The pulse-train is split: the intense infrared beam enters the Kerr liquid, the second is converted by SHG in a KDP-crystal to a weak green beam. It is possible to delay the green pulse relative to the infrared pulse (positive and negative delays are possible). The infrared beam induces birefringence. When both pulses travel through the cell the photodetector measures green light. When the Kerr effect is caused by molecular distortion, the plot intensity versus delay-time must be unsymmetric, for the damping time is in the order of some ten picoseconds[20, 21] (fig.16a). If the Kerr effect is an electronic effect, the curve must be symmetric (fig.16b), for the damping time is smaller by more than two orders of magnitude than the laser-pulse.Duguay and Hansen measured for nitrobenzene a curve similar to figure 17a, but for CS_2 a curve with an unsymmetry of about 10 psec. These measurements are not fully satisfying, for the pulse-structure is completely unknown. But assuring the worst case, that the "ghost field" is in the order of ten picoseconds (fig.17) a time resolution of about five picoseconds is attainable with an optical sampling-method. Therefore we decided to develop an ultrafast Kerr-gate and measure synchrotron-pulses by sampling methods. Since Duguay and Hansen measured an efficiency of about 20% we hope to measure synchrotron-pulses even at low currents.

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[18] G.Mayer and F.Gires: Compt. Rend. 258 (1964), 2039

[19] M.A.Duguay and J.W.Hansen: An Ultrafast Light-gate, Appl.Phys. Lett. 15(1969), 192

[20] R.G.Brewer and C.H.Lee: Self Trapping with picosecond Light-pulses Phys. Rev. Lett. 21 (1968), 267

[21] R.G.Brewer and A.D.McLean: Distortion of Molecules in Intense electric Fields, Phys. Rev. Lett. 21(1968), 271

TECHNICAL REALISATION OF AN APPARATUS FOR MEASURING ULTRASHORT SYNCHROTRON LIGHT PULSES BY OPTICAL SAMPLING METHODS

In our final apparatus a continuously pumped Nd-YAG-laser (Yttrium-aluminium-garnet doped with Nd-ions) will emit pulses of constant intensity. The repitition-frequency of the laser-pulses is slightly different from the repitition - frequency of the synchrotron-pulses (sampling condition). The modes are locked by a RF-feedback equipment discussed by Huggett [22](fig.18). The amplifier selects the beat-frequencies between different modes (approximatly 500 Mhz). If the phases are correct, the signal is amplified by the intracavity modulator (for instance KDP). Otherwise the modulator disturbs the oscillating modes until the phases of the modes are correct. With this apparatus pulses of 20 psec pulse-length will be obtained. In order to obtain pulses in the order of 2 psec the 20psec-pulses are compressed outside the laser-cavity by a method described by Treacy[23,24,25]: a light pulse can be described by a varying carrier frequency throughout the pulse [26](" chirping " of the pulse). The Treacy-apparatus consists of two gratings with frequency-dependent diffraction angle (fig.19). Two different frequencies run along paths of different pathlengths. Since the frequencies at the front-side of the pulse hav e to pass longer optical ways than the frequencies at the trailing edge of the pulse the pulse is compressed. With this apparatus it seems possible to obtain pulses with pulse-lenghts of 2 psec. The compressed pulse enters a Kerr-cell and "cuts out" 2 psec of the synchrotron-pulse. The sampled pulse is detected by a photomultiplier (fig.20).

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The authors wish to thank Prof.Dr.K.P.Mayer, B.Hausherr and H.J. Keller from the Institute of Applied Physics, University of Berne, and Dr.R. Dändlicker from PHilips, Eindhoven, for helpful discussion.

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[22] G.R.Huggett: Mode-Locking of CW Lasers by Regenerative RF Feedback Appl.Phys. Lett. 13 (1968), 186

[23] E.B.Treacy: Compression of picosecond light-pulses, Phys.Lett. 28A (1968), 34

[24] E.B.Treacy: Optical pulse Compression with Diffraction Gratings, IEEE J.Quantum Electronics, QE-5 (1968), 454

[25] J.A.Giordmaine, M.A. Duguay and J.W.Hansen: Compression of optical pulses, IEEE J.Quantum Electronics , QE-4(1968),252

[26] see for instance: E.Mollwo and W.Kaule: Maser and Laser, Bibliograph.Inst. Mannheim, Hochschultaschenbücher

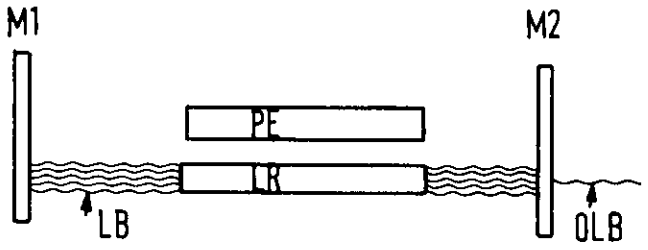

Fig. 1: Schematic plotting of a laser: LR rod with laser-active material, PE pumping-equipment, for instance a flash-lamp, M1: mirror with about 100% reflectivity, M2 mirror with about 90% reflectivity, LB laser beam inside the Fabry-Perot resonator, OLB: laser beam outside the cavity.

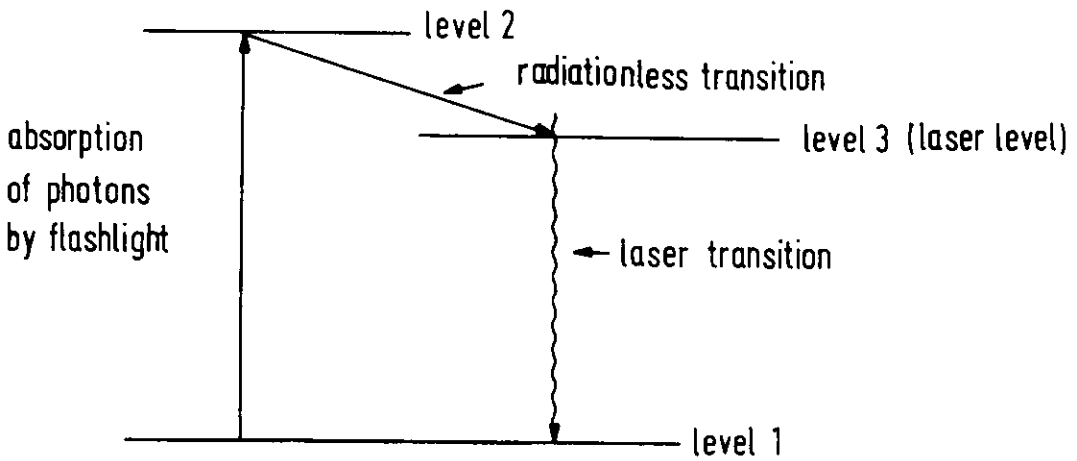

Fig.2: Simplified energy-scheme of a laser-transition

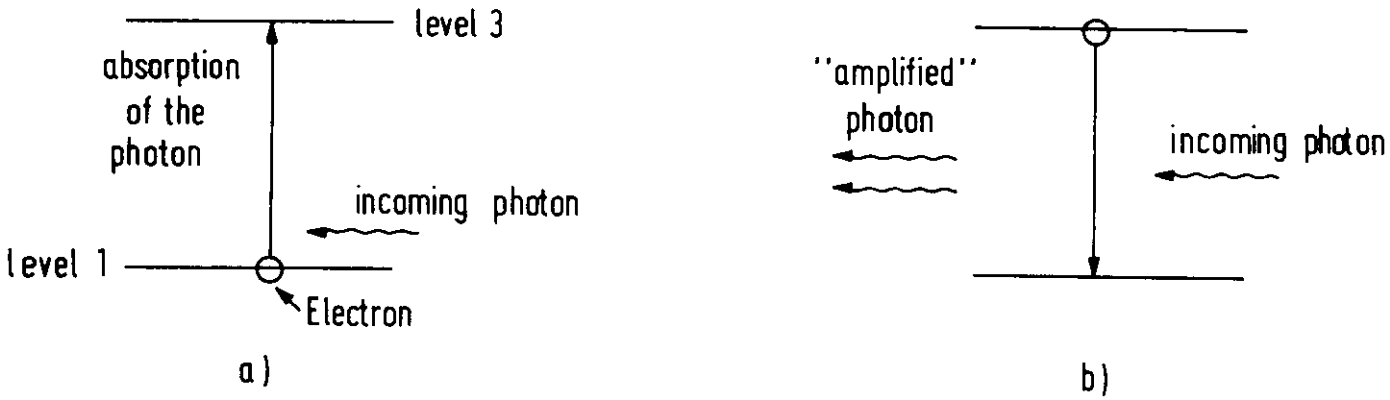

fig.3 : a) absorption of the laser-radiation by a noninverted electron.
b) stimulated emission of a photon.

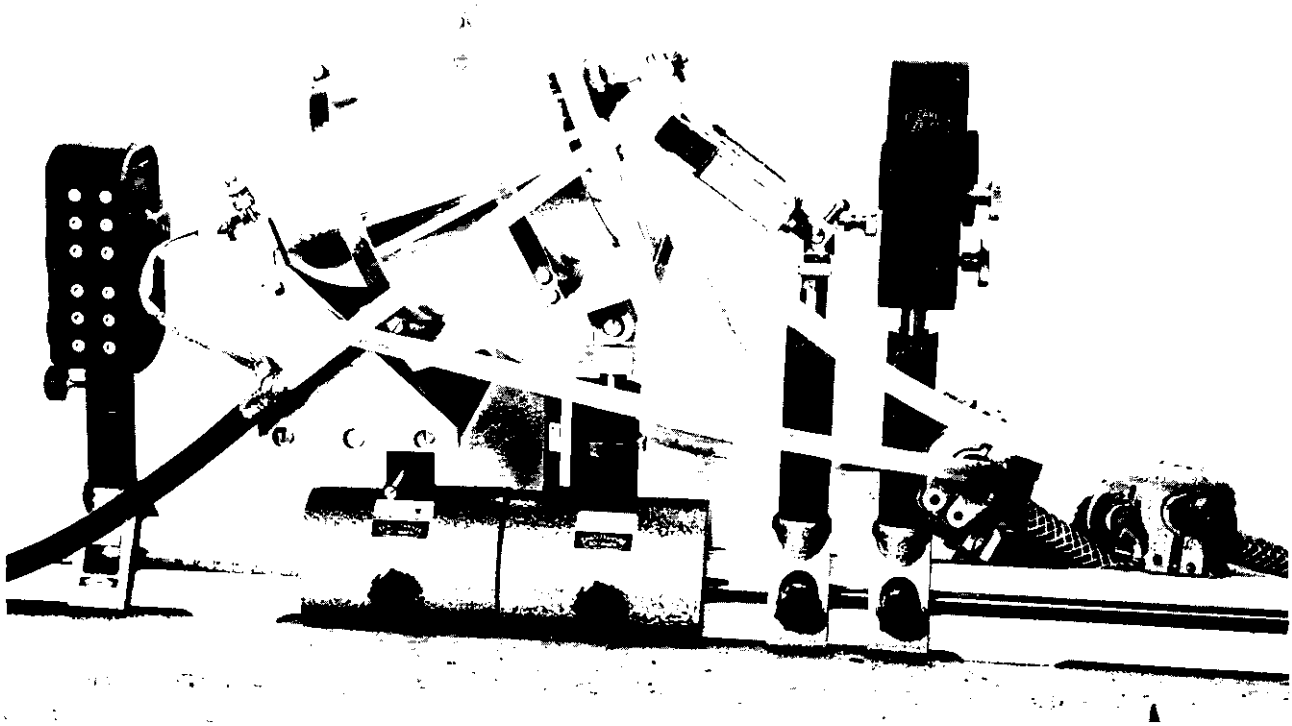

fig.4 : Nd-glass-laser. Inside the laser-head (middle of the picture) is the laser-rod and the flash-lamp. The laser head is inclined to obtain a linearly polarized laser-beam.

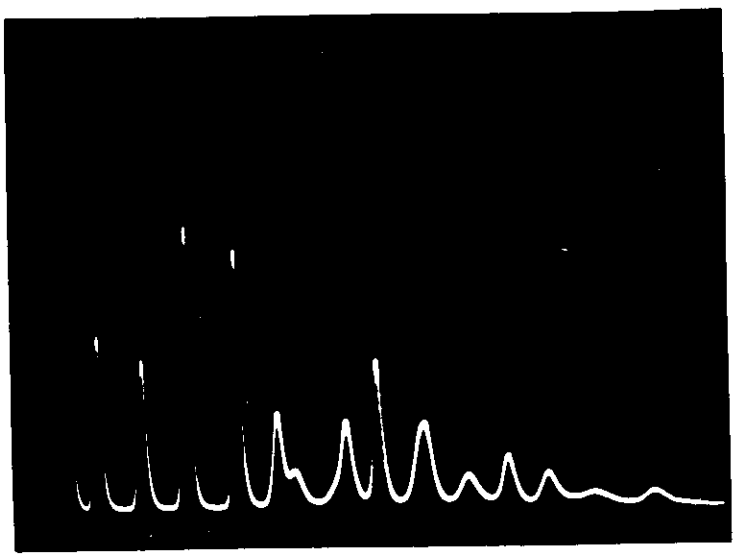

fig.5 : "Spiking" of a broadband Nd-glass-laser

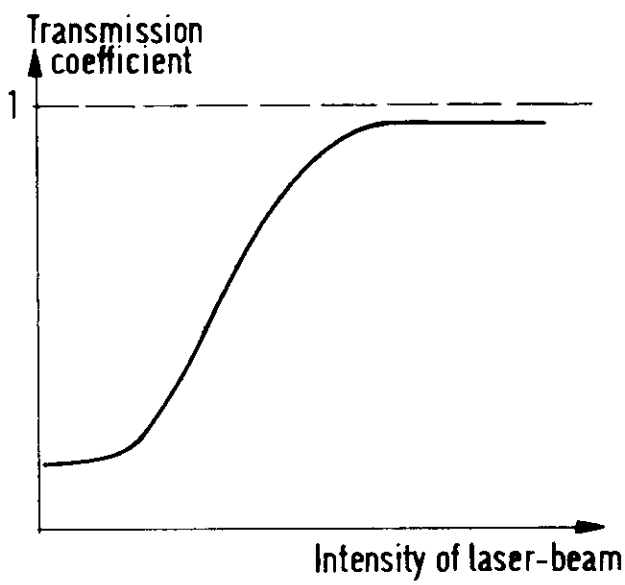

fig.6 : Transmission of a nonlinear liquid

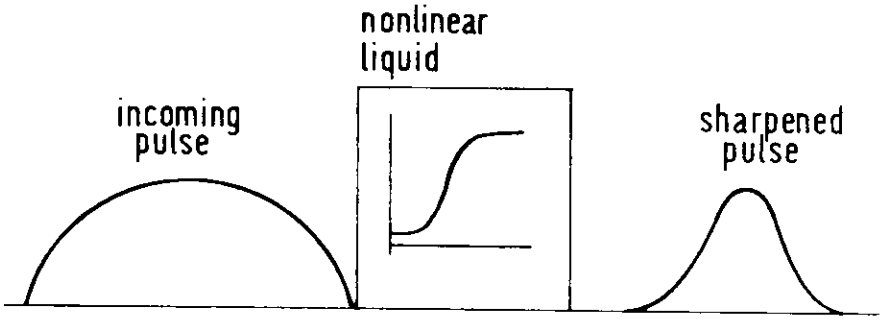

fig. 7 : Sharpening of intense laser pulses by nonlinear liquids

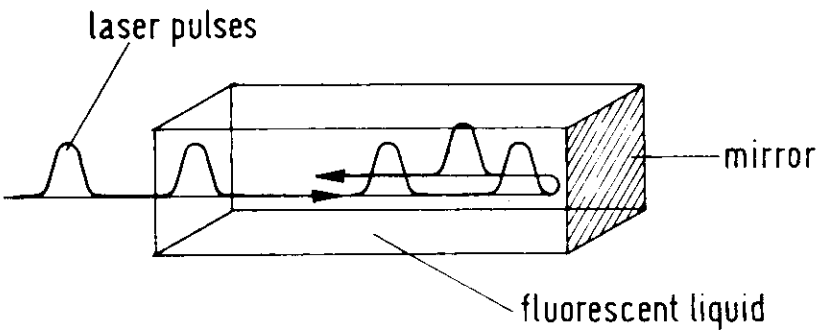

fig. 8 : Standing light-wave in a fluorescence-cell

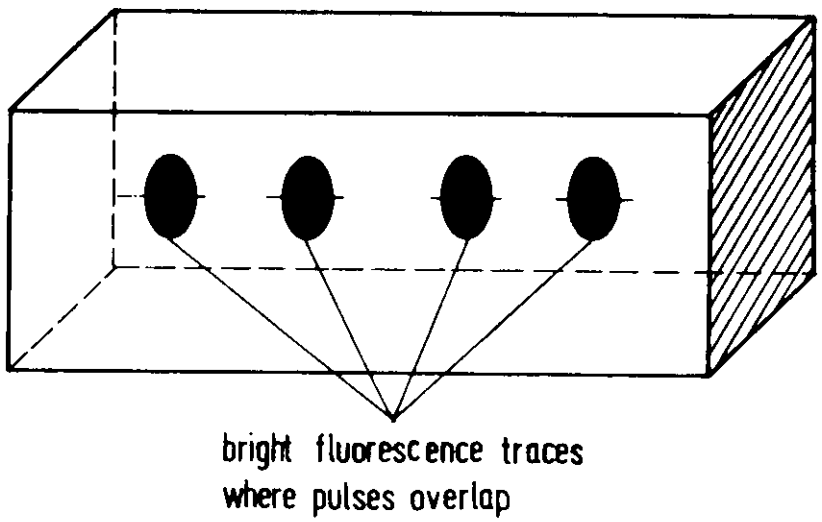

fig. 9 : Fluorescence trace of a pulse-train in nonlinearly absorbing liquid

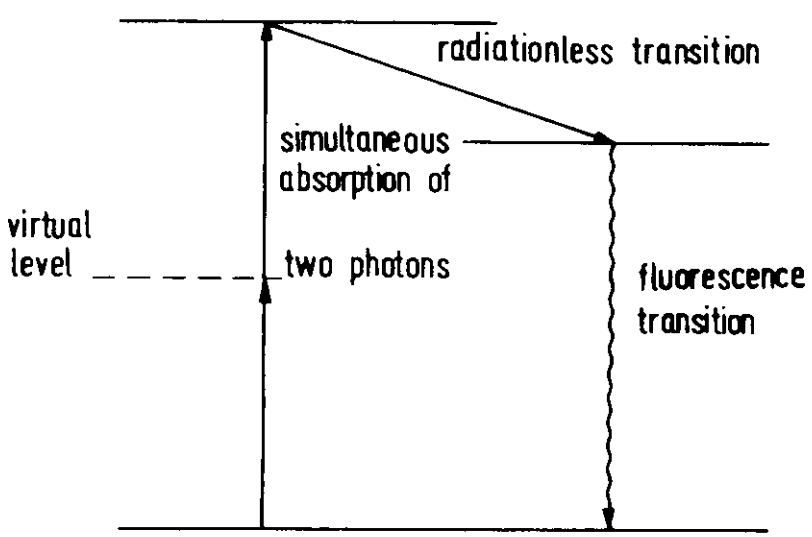

fig. 10 : Schematic plot of two-photon absorption

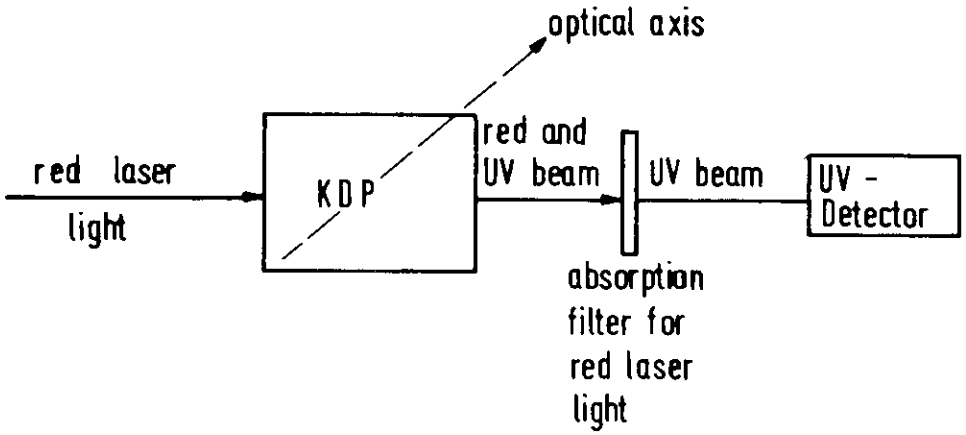

fig. 11 : SHG in nonlinear crystals

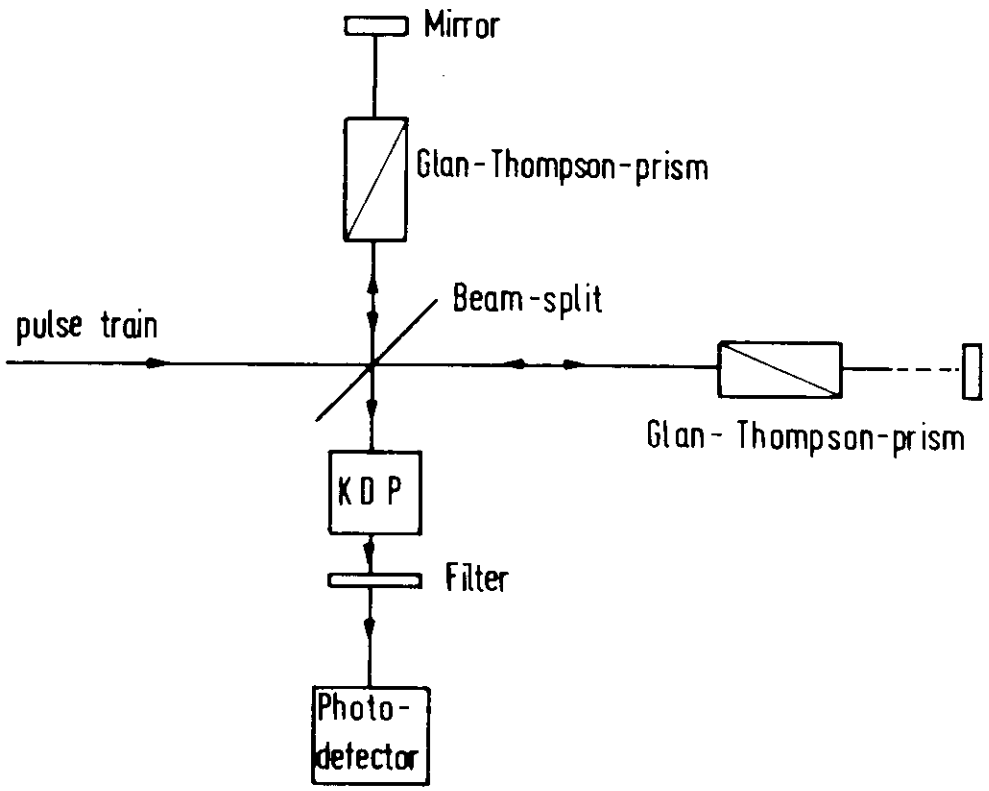

fig.12 : Method of measuring ultrashort pulses by SHG.

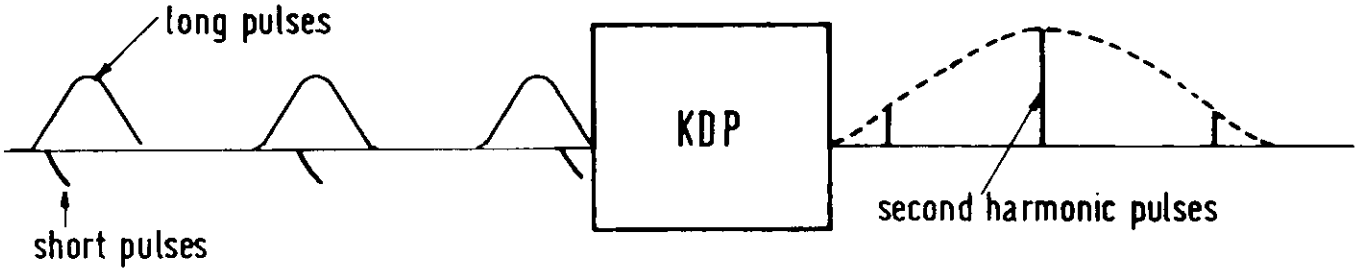

fig. 13 : Optical sampling of a pulse train

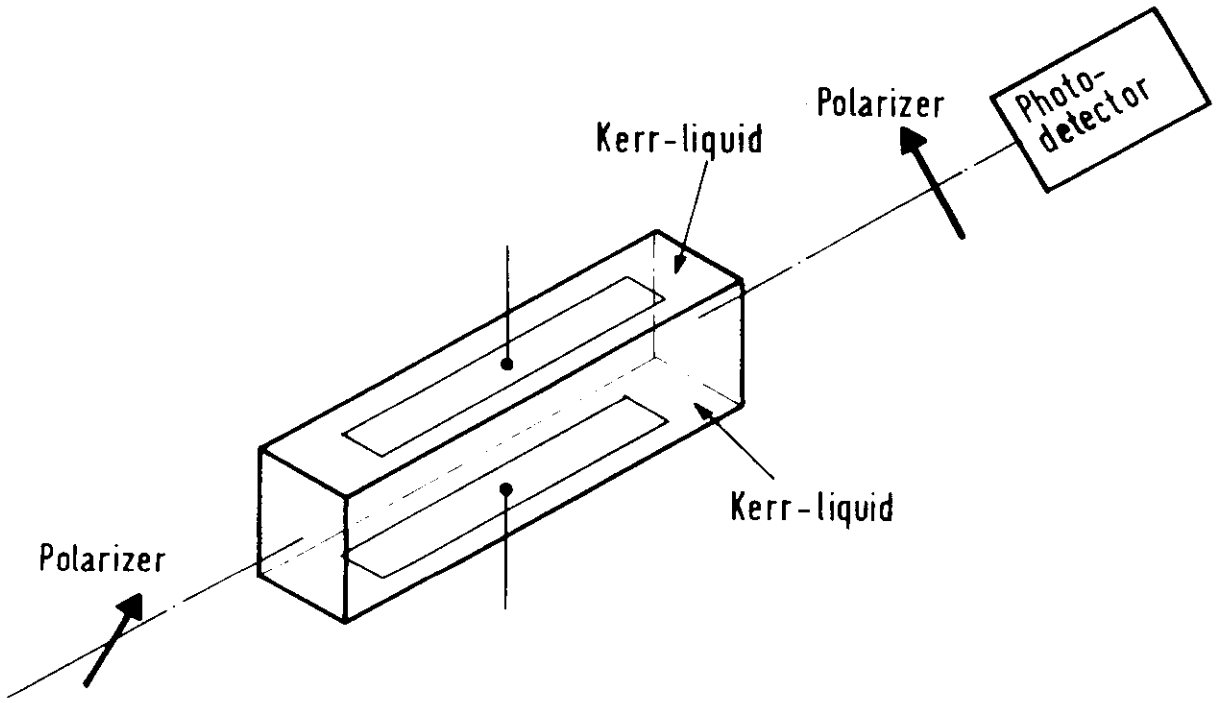

fig. 14 : System for measuring electrical Kerr-effect

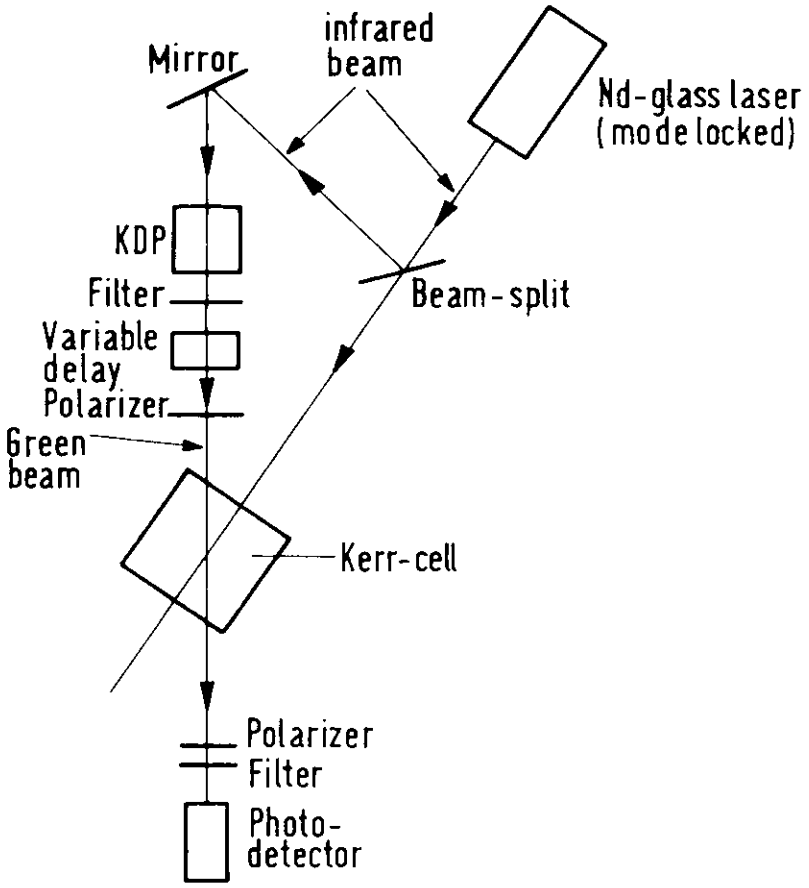

fig. 15 : System of measuring optical Kerr-effect in the picosecond range

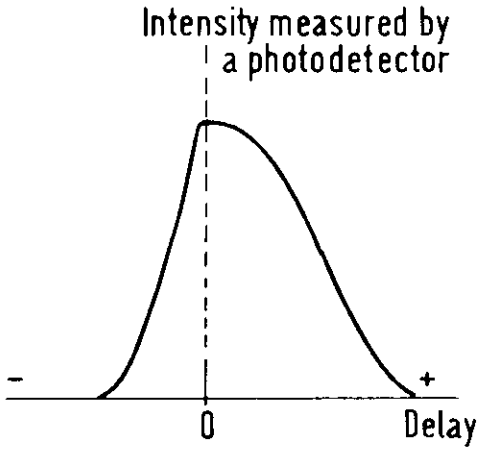

fig.16a

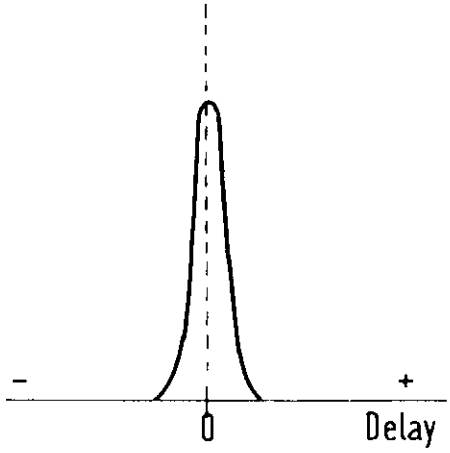

fig. 16b

fig. 16 : plot intensity versus delay-time in the picosecond range for molecular (16a) and electronic (16b) Kerr-effect.

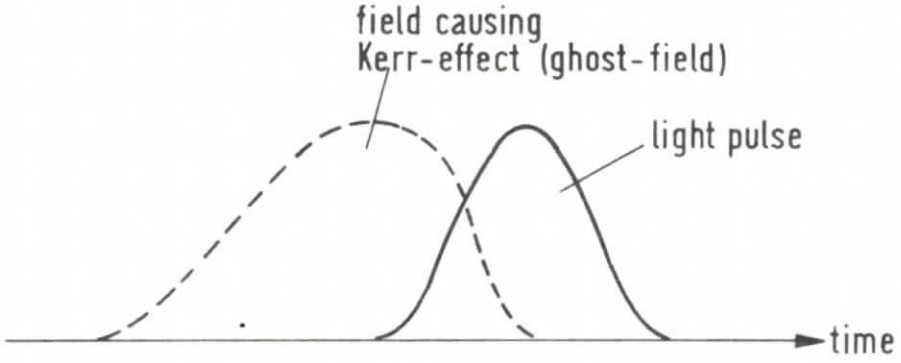

fig. 17 : "ghost-fields" causing optical Kerr-effect in the picosecond-range

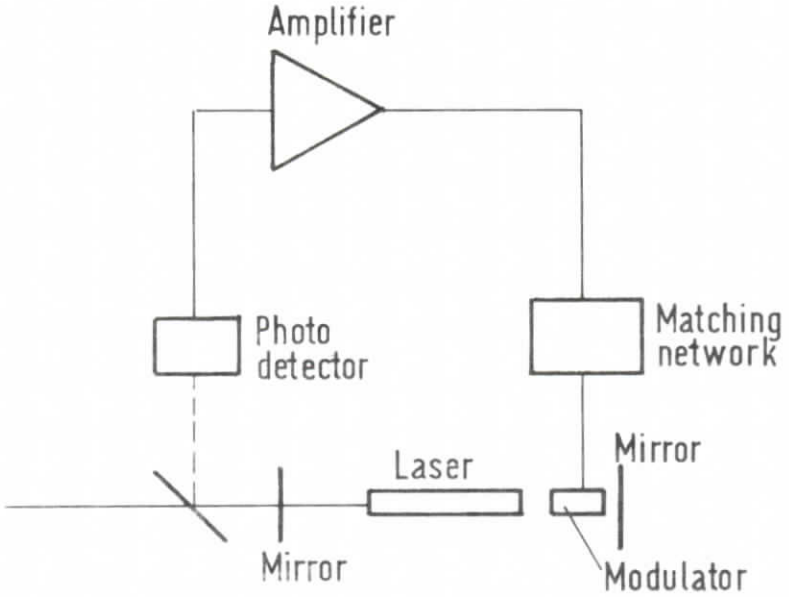

fig. 18 : Mode-locking of CW-Laser by RF-feedback

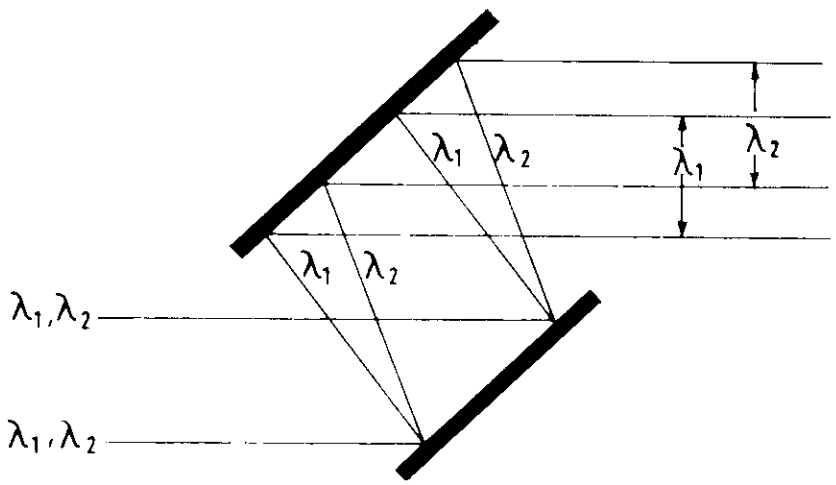

fig. 19 : Pulse-compression of chirped pulses by two gratings

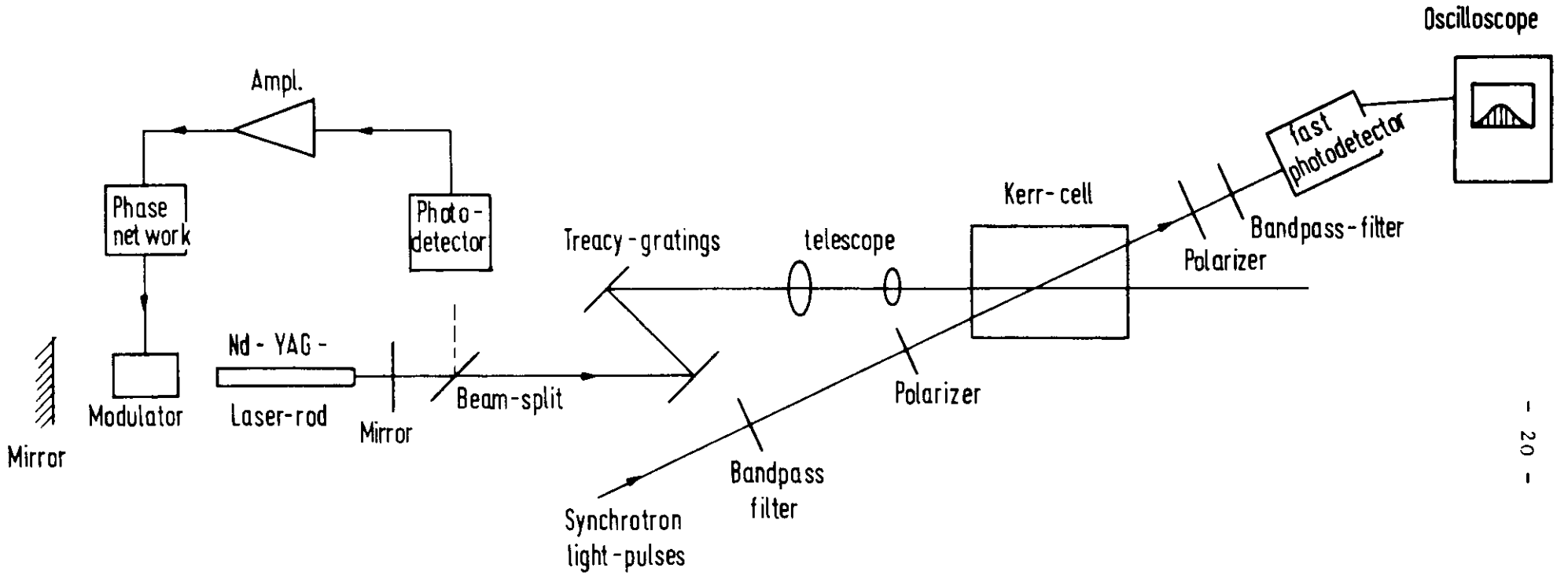

fig.20 : Final apparatus for measuring synchrotron pulses in the picosecond range