Nuclear Instruments and Methods in Physics Research A286 (1990) 1-8
North-Holland

A SOURCE OF POLARIZED ELECTRONS BASED ON PHOTOEMISSION OF GaAsP

W. HARTMANN, D. CONRATH, W. GASTEYER, H.J. GESSINGER, W. HEIL, H. KESSLER, L. KOCH and E. REICHERT

Institut für Physik, Johannes Gutenberg Universitat Mainz, P.O. Box 3980, Mainz, FRG

H.G. ANDRESEN, T. KETTNER and B. WAGNER

Institut für Kernphysik, Johannes Gutenberg Universität Mainz, P.O. Box 3980, 6500 Mainz, FRG

J. AHRENS

MPI für Chemie, P.O. Box 3060, 6500 Mainz, FRG

J. JETHWA and F.P. SCHÄFER

MPI für Biophysikalische Chemie, 3400 Göttingen, FRG

Received 12 July 1989

The source described is based on photoemission of electrons from 100-$GaAs_{0.62}P_{0.38}$ activated to negative electron affinity. It is built to inject a beam of polarized electrons into the 350 MeV linear accelerator in Mainz. It is capable of delivering a mean current of 28 μA spin-polarized longitudinally to a degree of 0.44. The lifetime of the cathode under operational conditions is better than 200 h. The source was successfully run in a parity experiment, in which the analysing power of quasielastic scattering from beryllium for longitudinally polarized electrons was measured.

1. Introduction

The source presented in this work was built for injecting a beam of polarized electrons into the 350 MeV linear accelerator in Mainz. It was successfully run in a parity experiment in which the analysing power of quasielastic scattering from beryllium for longitudinally polarized electrons was measured at 300 MeV [1-3].

The source is based on photoemission of electrons from a III-V-semiconductor cathode activated to negative electron affinity (NEA) [4,5]. The emission process is the most powerful way to produce polarized electrons nowadays and was applied for the first time for injection into an accelerator at SLAC [7,9] in several celebrated experiments on deep inelastic scattering of polarized electrons from deuterium at collision energies around 20 GeV.

The present source follows the SLAC design, but attacks two main problems that are encountered in running III-V-photocathodes in an accelerator source in somewhat different ways.

One problem is the finite cathode lifetime due to NEA deterioration. This work uses $GaAs_{0.62}P_{0.38}$ instead of GaAs commonly employed. The ternary semiconductor $GaAs_{0.62}P_{0.38}$ is a relative of GaAs with respect to bandstructure. It emits polarized electrons on irradiation with circularly polarized light of a frequency just above absorption threshold as GaAs cathodes do [10,11]. It is also capable of producing electrons spin-polarized up to a degree around 0.40. But it is easier to prepare and to sustain a negative value of electron affinity on a GaAsP surface, because it has a larger band gap [12,13]. In our experience it is therefore easier to achieve long cathode lifetime with GaAsP than with GaAs.

The other problem is peculiar to pulsed accelerators with high peak currents. Proper pulse shaping of injected current is the problem here. Flash lamp pumped dye lasers are the only monochromatic light sources used today, that are powerful enough to produce pulsed, polarized electron currents with amplitudes above say 100 mA by photoemission from GaAs or GaAsP. Unfortunately the form of light pulses emitted by such lasers does not meet the requirements of an accelerator. The current pulse of electrons injected into an accelerator should be of rectangular shape. Otherwise the beam loading of hf-sections in the accelerator varies with time which may result in severe energy variations of the final beam.

0168-9002/90/$03.50

In the present source the light power transmitted to the cathode is controlled by a pockels cell, that is part of a feedback system comprising a Rogowski coil pickup of emission current and a fast electronic driver amplifier essentially. This allows the light pulses to be shaped into a form, that will ensure proper operation of the linac.

Some effort has been made to enable the sign of the spin polarization of the electron beam produced to be changed without affecting its current and phase space. This was necessary for detecting the very tiny helicity dependence of quasielastic electron beryllium cross section in the parity experiment mentioned above [1–3]. The relative change in emission current due to switching its helicity is only 6×10^{-6} as described below.

The paper is organised as follows: section 2 sketches an overall view of the source. In section 3 the photoemission of electrons from $GaAs_{0.62}P_{0.38}$ is described while section 4 discusses the details of light optics and pulse shaping. Section 5 gives a summary.

2. Survey of the source of polarized electrons

Fig. 1 sketches an overall view of the source built in the present work, while fig. 2 shows some details of the cathode chamber. Besides minor changes in the cathode–anode distance the electron gun displayed in fig. 2 is a copy of a SLAC design [7] applied in the above mentioned parity experiments performed in Stanford [9].

The GaAsP-photocathode (fig. 2) is irradiated with circularly polarized 643 nm light entering the gun cham-

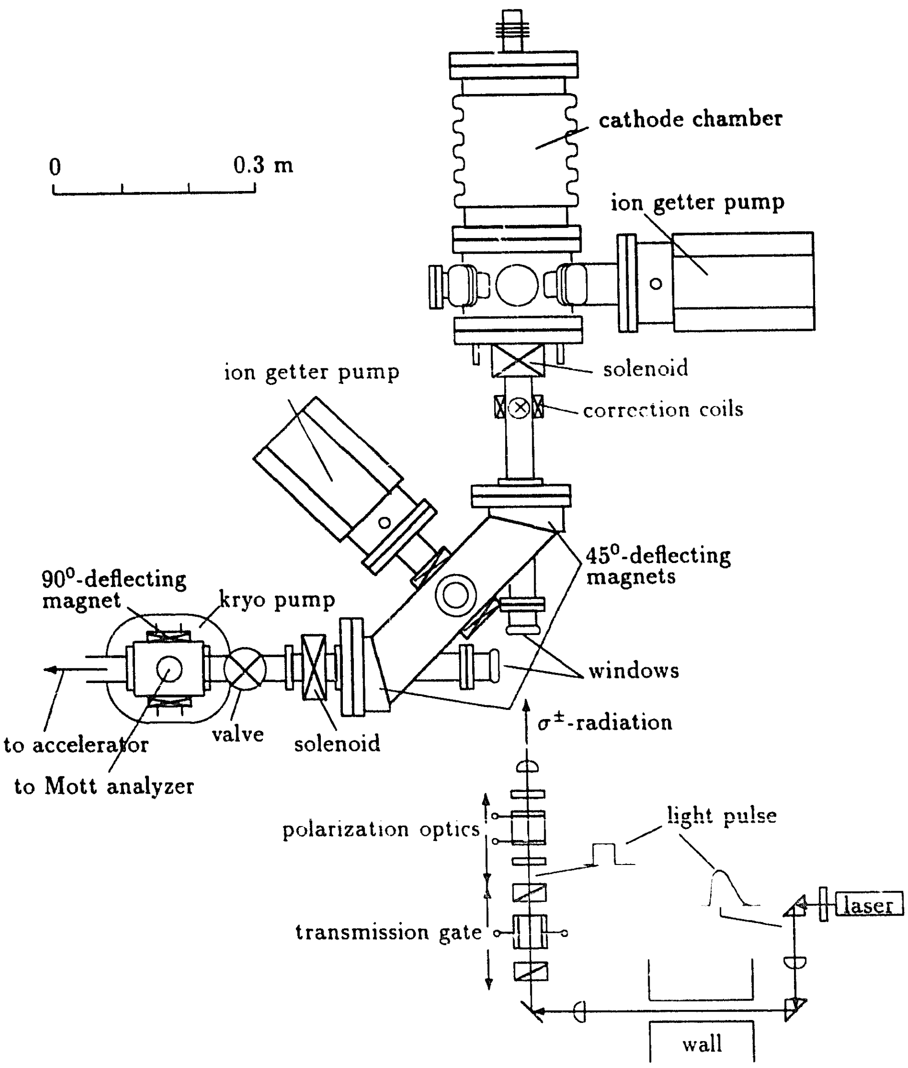

Fig. 1. Source of polarized electrons (side view). Elements of light optics are not to scale.

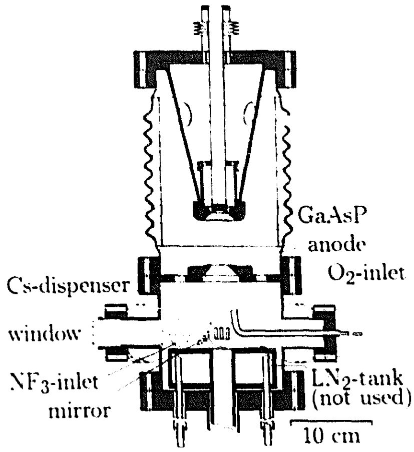

Fig. 2. Gun of polarized electron source.

ber through a glass-window from below. The light source is a flash lamp pumped dye laser working at 643 nm with a repetition frequency of 50 Hz [15] that is locked to the repetition frequency of the linac hf-modulators. The laser produces a spot of 8 mm diameter at the cathode.

Circular light polarization is achieved with the help of a polarization optics that is discussed in section 4. An optical transmission gate serves for pulse forming purposes in a way, that is also described in section 4.

The crystal emits electrons with spin orientation that is antiparallel to that of the photon spins preferentially [4,5,10,11]. The electrons are accelerated to the injection energy of the accelerator of 44 keV. The gun optics has been reexamined with help of an electron trajectory program published by Herrmannsfeldt [14]. This computer simulation gives an emittance of 23π mm mrad at the anode hole of the beam produced, the value of which is small enough to meet the acceptance phase space of the accelerator. The electrons leaving the gun are transmitted to the linac by a beam line consisting essentially of a solenoid that forms a parallel beam, of two magnetic dipoles deflecting the beam through 45° each, and a second solenoid, that focusses the beam to the accelerator entrance. Several correction coil pairs serve to adjust the beam position.

The transmission of electrons from the cathode to the entrance of the linac is better than 98%. A good transmission is important not only to save current but also to achieve a good lifetime of the cathode. Electrons hitting solid surfaces desorb atoms or molecules, which may poison the NEA layer of the cathode. The cathode will be killed almost for certain, if the beam scrapes an electrode in the neighbourhood of the cathode.

All parts of the source are compatible with ultra high vacuum requirements. A residual gas pressure in the lower 10^{-10} mbar regime is essential for a good lifetime of the cathode.

The polarization of the electrons may be analyzed by deflecting the beam towards a side arm (not shown in fig. 1) comprising a Wien filter and a Mott analyser. Actually during the parity experiment mentioned above the spin polarization of the beam was not monitored at this place, but at the final energy at the scattering target using a Compton polarimeter [21,22].

3. Preparation of NEA-$GaAs_{0.62}P_{0.38}$-photocathodes

The base cathode material was supplied by General Instrument Corporation, Optoelectronic Division, Bruxelles, Belgium. This material is used in the semiconductor industry to fabricate light emitting diodes emitting in the red. The wafers consist of GaAs-slices oriented (100) and covered on one surface with a thin epitaxial layer of n-conducting $GaAs_{0.62}P_{0.38}$ ($n = 8 \times 10^{16} cm^{-3}$). Discs of 1.25 cm diameter were cut from the wafers by Battelle Institut e.V., Frankfurt, FRG.

Heavy p-doping of the cathode surface is a prerequisite to achieve negative electron affinity in the preparation procedure described below [12]. A conversion to p-conductivity (4×10^{19} cm^{-3} Zn) at the surface of the cathode discs was also done at the Battelle Institut.

Cleaning and preparation of the negative electron affinity of the cathode samples is done in similar way as in other laboratories [6–8,25]. To start with a crystal is etched in a 8 : 1 : 1 mixture of conc. H_2SO_4, 30%H_2O_2, and H_2O for 15 s, then rinsed in H_2O and finally dried by blowing argon on to the sample surface. Immediately afterwards the cathode is mounted at its place in the gun, which immediately is evacuated. The whole source assembly is baked at 250 °C for a week or so. The cathode is heated separately by a heater element introduced from above into the central tubing of the chamber (fig. 2) and held at an elevated temperature of approximately 300 °C during bakeout. Final base pressure in the gun chamber is around 1×10^{-10} mbar.

NEA preparation starts with heat cleaning the sample at 600 °C overnight in order to remove oxides and carbon from the surface [18]. Back to room temperature the cathode surface is coated with a submonolayer of cesium [13] by heating a Cs-dispenser (SAES Getters, Milano, Italy) welded on an electrical feedthrough in a side flange of the gun chamber (fig. 2). During the preparation process the crystal is illuminated with white light or light from a HeNe-laser via a window and mirror shown in fig. 2, and the current of photoelectrons emitted is registered. Cesiation is stopped as soon as the photocurrent goes through a maximum. Further processing is done by admitting either O_2- or NF_3-gas into the cathode chamber.

O_2 is introduced by heating a thin-walled silver tubing that is weakly permeable for oxygen at temperatures above approximately 400 °C [19]. The oxidation

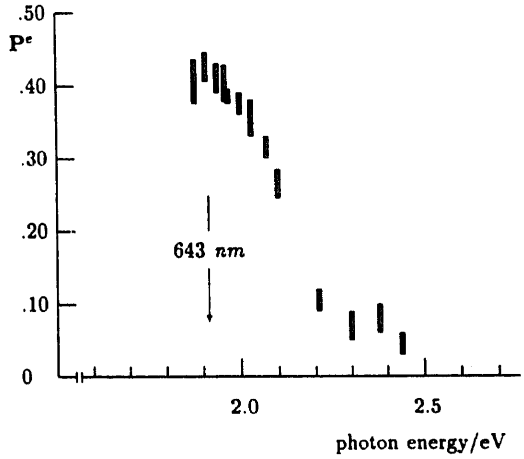

Fig. 3. Spin polarization spectrum of electrons emitted by NEA-$GaAs_{0.62}P_{0.32}$. A photon energy of 643 nm radiation is indicated.

process results in a further increase of photocurrent and is continued until a new maximum of electron current is reached. Cesiation and oxidation steps may be repeated several times (sometimes called the jo-jo-technique), but the current gain per step decreases rapidly.

NF_3 in place of O_2 in the above sketched procedure has been proposed by Sinclair on a workshop on Polarized Electron Sources held at SLAC in 1983 [20]. It is believed, that NF_3 decomposes at the cesiated cathode surface and pure fluorine is embedded in the surface cesium layer. In our apparatus NF_3 may be admitted to the gun chamber via a needle valve not shown in fig. 2. We do not see a significant difference in cathode performance if we prepare with O_2 or NF_3 respectively. Gasteyer [13] however finds a slightly lower value of electron affinity in the case of fluorine preparation, which led us to prefer NF_3 in NEA-activation.

Reactivation of a poisoned cathode may be done by repeating the NEA procedure starting with heat cleaning at 600 °C overnight.

$GaAs_{0.62}P_{0.38}$ cathodes prepared in this way have a quantum efficiency of roughly 0.01 electrons per photon for 643 nm radiation. The electrons emitted are spin polarized to a degree around 0.4 at this wavelength on

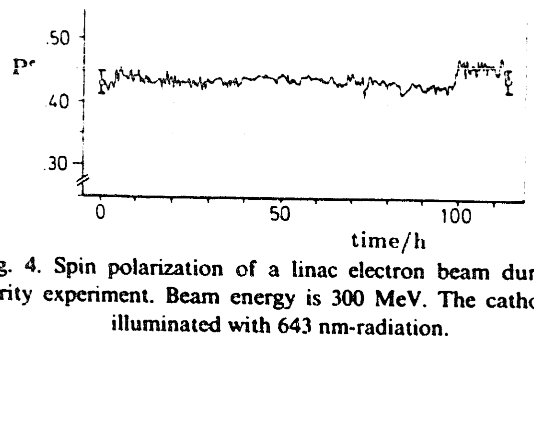

Fig. 4. Spin polarization of a linac electron beam during a parity experiment. Beam energy is 300 MeV. The cathode is illuminated with 643 nm-radiation.

irradiation with circularly polarized light [10,11]. This is seen in fig. 3, which shows the spin polarization spectrum of electrons emitted from a $GaAs_{0.62}P_{0.38}$-sample measured in a separate investigation in our laboratory.

Actually the cathode which has been operating in the present source for five years now produces a beam of electrons polarized longitudinally to a degree of 0.44. Fig. 4 shows as an example the spin polarization of the electron beam produced by the present source as a function of time in the course of an experiment at the Mainz linac. The beam is accelerated to 300 MeV in this case and its spin polarization is measured by the above mentioned Compton polarimeter [21,22].

4. Light optics

Fig. 5 sketches the set-up of light optics used to produce a circularly polarized light beam illuminating the cathode.

4.1. Laser

The light source is a flash lamp pumped dye laser, that was developed at the Max Planck Institut für Biophysikalische Chemie in Göttingen [15]. A dye-solution of 2×10^{-4} mol/l Sulforhodamin B in H_2O is used. 4 vol% of the deaggregating agent Ammonyx and 5×10^{-4} of the triplet quencher cyclooctratetraene is added to the solution. With this combination the system lases at 643 nm, which nicely fits to the maximum of electron spin polarization to be expected from a $GaAs_{0.62}P_{0.38}$ cathode (fig. 3).

The dye reservoir of the laser was enlarged to a capacity of 45 l to get a long run time. A typical light pulse after some hours operation is shown in fig. 6(a). Its amplitude is 4.4 kW in this case, FWHW is 5 μs, and the width at its base is 9 μs. A freshly prepared laser

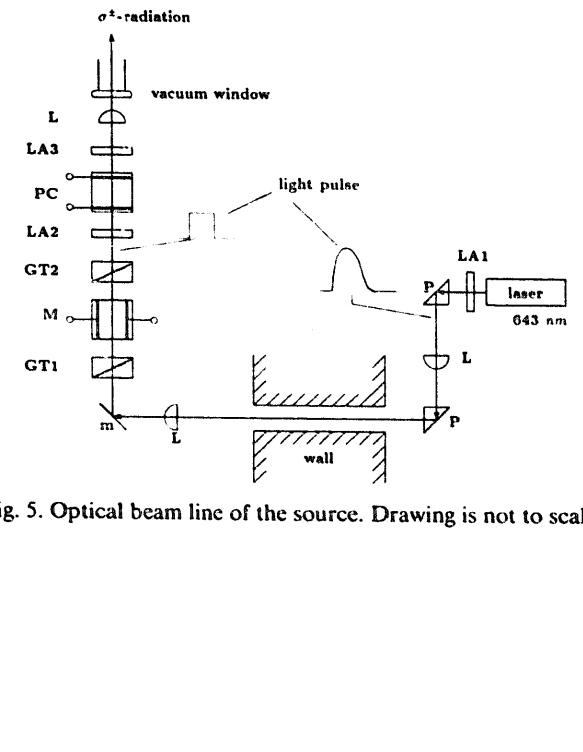

Fig. 5. Optical beam line of the source. Drawing is not to scale.

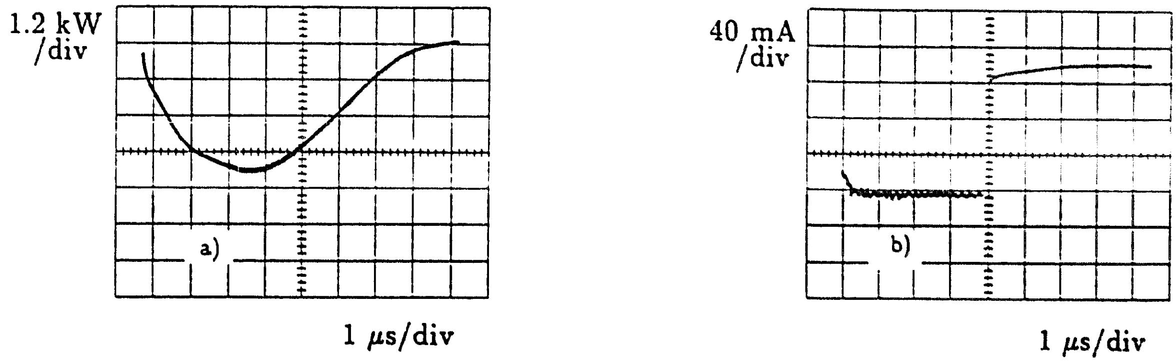

Fig. 6. (a) Light pulse of laser. (b) Pulse of electron current emitted shaped by light power control.

(fresh dye solution, new lamps) delivers peak powers up to 10 kW. In 12 h of continuous operation at 50 Hz the peak power drops to 3 kW typically, because of flash lamp and dye deterioration. Replacement of dye brings it up to 5 kW again, which decreases to 2 kW in another period of 12 h. In any case there is ample laser power to emit peak currents of 100 mA and more from the source even if there is some loss in the optimal beam line.

In spite of this the dye is routinely replaced every 12 h and the lamps every 24 h, because the pulse-to-pulse stability gets worse with prolonged time. The peak laser power L varies statistically. A freshly prepared laser shows a relative variation of $\Delta L/L = 3\%$ (one standard deviation), while the variation grows up to 10% typically in a 12 h run. 10% is the limit that can be handled by the light stabilising circuit described below.

The laser beam is linearly polarized. It has an elliptical cross section with semi-axes of 4 mm and 3 mm at its resonator exit, and a divergence of 5 mrad and 8 mrad, respectively. It is sent over a path of about 3 m length via two totally reflecting prisms P, a channel in the wall of the accelerator tunnel, two lenses L and a mirror m to the entrance of the stabilising and polarizing optics, whose first element is a Glan prism GT1. In the path there is a half wave plate LAI, that is used to adjust the light power transmitted by adjusting the angle between the plane of linear polarization of the light beam and the polarisator plane of Glan prism GT1.

4.2. Light power control and pulse shaping

The linac expects a current pulse at injection with a time dependence that is rectangular in shape. Risetime and falltime should be around 30 ns, pulse duration is to be 4 μs, and the top should be flat within 2%. Deviations from this ideal pulse form lead to a varying load of the hf-sections in the linac during acceleration time with the consequence of varying final energy of the beam.

Glan prisms GT1, GT2, together with the modulator M constitute a fast optical transmission gate, that is used to shape the light pulse transmitted to the cathode. Actually M is a transverse Pockels cell (model LM 0202

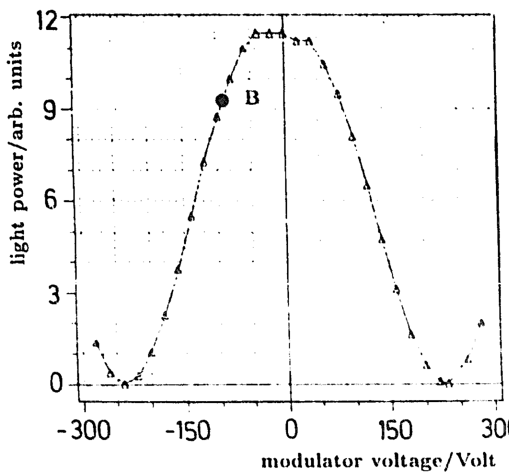

Fig. 7. Transmission of optical gate consisting of prisms GT1, GT2 and modulator M as a function of modulator voltage. B indicates the bias of the gate.

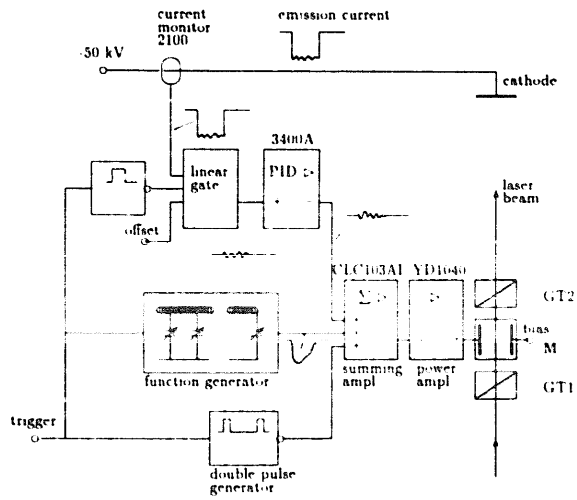

Fig. 8. Driver circuit of the optical transmission gate.

modulator, Gsänger Optische Komponenten, Planegg, FRG). The polarization planes of the prisms are aligned to each other and are inclined by an angle of 45° with respect to the optical axis of the cell. The light transmission of this system is proportional to

$$\cos^2(\pi U/2U_{\lambda/2}), \qquad (1)$$

with U = cell voltage and $U_{\lambda/2}$ = half wave retardation voltage (fig. 7). A negative bias is applied to the cell the bias point being indicated in fig. 7.

The cell is controlled by an electronic circuit as sketched in fig. 8. The cell driver is made up of a summing amplifier CLC103AI and a fast power stage consisting of a lighthouse tube YD1040 operated in grounded grid mode. Three signals are applied to the summing input of the driver.

On the one hand the driver is part of a negative feedback loop with the task of damping as much as feasible photocurrent excursions, that go beyond a certain preset level. For that purpose a voltage signal proportional to the current of electrons emitted by the photocathode is derived with the help of a Rogowski coil (Model 2100 current monitor, Pearson Electronics, Palo Alto, USA) enclosing the cathode lead. That part of the signal amplitude that surpasses a given offset voltage is amplified by an operational amplifier 3400A and fed to one entrance of the driver. The open loop gain at low frequencies is 15 approximately. Its upper frequency is 8 MHz only. A greater bandwidth resulted in oscillations due to delay times in connecting cables and other electronic components.

The feedback system alone could not damp in the current fluctuations below the 2% level. Therefore the light was preregulated in a way that in principle has already been applied in controlling the SLAC source [7]. A voltage pulse is generated in a pulse-forming network consisting of a transmission line-like combination of capacitors and inductances and fed to the driver. The shape of that additional signal is adjusted in such a way that it counteracts excursions of the light power above a preset level. This scheme works as long as the laser pulse form is fairly stable.

The third signal comes from a pulse generator delivering pulse pairs with 4 μs separation. It is fed to a third entrance port of the driver circuit. The pulses shut the optical transmission gate at times during start and end of the laser shot. In this way steep rise and fall times of the transmitted light are achieved.

All three steps together produce current pulses with a top, that is flat within 2% and that rises and falls respectively in less than 30 ns (fig. 6(b)). Pulse-to-pulse stability is around 3×10^{-3} as long as the primary fluctuations are not worse than 10%.

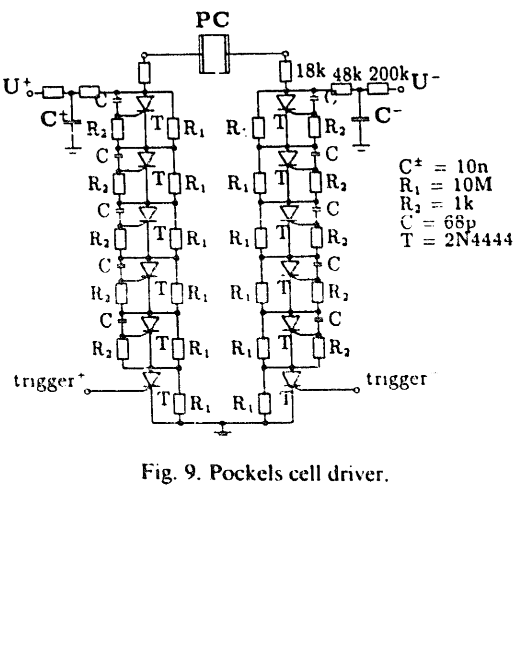

Fig. 9. Pockels cell driver.

4.3. Switching of circular light polarization

Circular light polarization is achieved with the help of Glan prism GT2 followed by a longitudinal Pockels cell PC (model PZ 16, Gsänger Optische Komponenten, Planegg, FRG) used in quarter wavelength retardation mode (fig. 5).

The cell is adjusted with respect to the optical beam line by a procedure that is described in detail in [16,17].

The sign of helicity of the beam transmitted is determined by the sign of quarter wave voltage applied to the Pockels cell. It is reversed by simply reversing the sign of the cell voltage.

Cell voltage is generated by the circuit shown fig. 9. It allows the sign of the cell potential to be chosen from pulse to pulse. Two condensers C^+ and C^- charged to voltages U^+ and U^- respectively are connected via resistors to the electrodes of the Pockels cell. Each may be discharged by a thyristor chain. Quarter wave retardation of the light beam is achieved by firing one thyristor chain at a time thereby shortcircuiting the corresponding electrode to ground potential. Firing one side produces σ^+-helicity while firing the other side produces σ^--helicity of the light beam transmitted.

The time constant of condenser discharge is chosen such that a short circuit lasts for 680 μs. After this time the discharge current falls below the value necessary to hold the thyristors in the conducting state and the condenser is recharged again. A thyristor chain is triggered 450 μs in advance of the light pulse to avoid disturbances due to ringing of the Pockels crystal.

4.4. Switching asymmetries

The spin polarization of the electrons emitted may be changed by switching the sign of circular polarization of the light illuminating the cathode. The ease of switching the sign of spin polarization is of great practical importance in actual scattering experiments. Very sensitive detection of spin dependent processes may be achieved by looking for scattering signals modulated in synchronism with a polarization switching. The sensitivity is limited however, if due to instrumental asymmetries not only the spin but also the current and phase space of the beam produced is affected by the switching process. Such instrumental asymmetries are minimised in three steps in the present set-up [23,24]

One is the careful alignment of the Pockels cell following the procedures described by Adams and Pettipiece, respectively, mentioned above [16,17].

In the next step the Pockels cell voltages $U^{\pm}$ are varied until the switching asymmetry in electron emission current

$$\frac{I^+ - I^-}{I^+ + I^-} \tag{2}$$

with I^+ = emission current with σ^+ light and I^- = emission current with σ^- light, reaches a minimum.

Further reduction of instrumental asymmetry was achieved by introducing a half wave plate LA3 between Pockels cell PC and the entrance window of the cathode chamber (fig. 5). We introduce that plate to minimize the influence of birefringence that may be present in the window because of tensions in the glass: a small component of linear polarization may be left in the light beam because of imperfect transformation to circular polarization in the Pockels cell PC. Such a linear component changes spatial orientation in phase with the switching of the Pockels cell voltage. In the case of birefringence in the window the light beam may be diffracted differently depending on the orientation of the residual linearly polarized component of the traversing light. The half wave plate LA3 is used to vary the mean orientation of such a linear component and is adjusted until electron beam fluctuations in synchronism with the pockels cell switching are minimized.

We finally arrived at an asymmetry of emission current that is correlated with the Pockels cell switching of

$$\frac{I^+ - I^-}{I^+ + I^-} = 6 \times 10^{-6}. \tag{3}$$

In the parity experiment mentioned above [1-3] the scattering signal is normalized to the primary beam current. This further reduces the contribution of emission current asymmetry to systematic errors in the measured parity violating analysing power to a negligible amount [3].

A third half wave plate LA2 was introduced for doing cross checks and searching for residual instrumental asymmetries in an actual scattering experiment. With the help of this plate the plane of linear polarization may be rotated through an angle of 90°. The correlation between the helicity of the light transmitted to the cathode and the sign of the Pockels cell voltage is reversed in this way. The asymmetry of scattered electron current due to the helicity dependence of the cross section should change sign in this case, if all other parameters are not changed.

5. Summary

The source described above was used in several runs at the Mainz electron linear accelerator each run lasting 10 days. The source had to be attached to the linac before each run, which took 3 days, and removed again at the end, which could be done in a time of 2 h. The essential parameters of the source are:

Peak current	$I_0 = 140$ mA,
Pulse duration	$\tau = 4$ μs,
Pulse repetition	$\nu = 50$ Hz,
Mean current	$\bar{I} = 28$ μA,
Polarization	$P = 44\%$,
Switching asymmetry	6×10^{-6},
Lifetime	$T \geq 200$ h.

Acknowledgements

We are indebted to E.L. Garwin from SLAC and to C.K. Sinclair from CEBAF for helpful advice concerning preparation technique of NEA surfaces and the construction of our gun assembly. We thank Dr. Jäger from the Batelle Institute for the careful redoping of GaAsP crystals and K. Beckhaus, H. Schreiber, and collegues for the precise machining of the apparatus. We gratefully acknowledge the help we got from R. Herr and his crew in attaching and running the source at the Mainz linac. The work was supported by the Deutsche Forschungsgemeinschaft as a project in the Sonderforschungsbereich 216.

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