DEUTSCHES ELEKTRONEN-SYNCHROTRON DESY

Prototype Polarized Electron Source Through Electron-Hydrogen Spin-Exchange

with Teflon Containment of Hydrogen and a Longitudinal Magnetic Trap

by

R. Krisciokaitis, W. K. Peterson

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PROTOTYPE POLARIZED ELECTRON SOURCE THROUGH ELECTRON-HYDROGEN SPIN-EXCHANGE

WITH TEFLON CONTAINMENT OF HYDROGEN AND A LONGITUDINAL MAGNETIC TRAP

Raymond Krisciokaitis[+], W. K. Peterson[++], DESY

Hamburg, Germany

Abstract:

A prototype polarized electron source has been constructed and results are reported. It is based on electron-hydrogen spin-exchange collisions using a longitudinal geometry electron trap and teflon coatings to contain the state-selected atomic hydrogen target. This scaled-down prototype is compatible with an electron linac and produces an extracted pulse of about 10^7 electrons/μ sec with about 60% polarization and 50-60 Hz repetition rate. Construction of a more intense (10^{10} or more electrons per pulse) full scale device based upon this technique is also discussed. The average measured total electron-hydrogen spin-exchange crossection for 5-10 eV electrons is estimated to be in the range 0.5-1.55 x 10^{-15} cm^2.

+ Address in 1974: C-E, Comb. Div., Nuclear Power Dept., Windsor, Conn., USA

++Present Address: Chemistry Dept., The John Hopkins University, Baltimore Md.
21218 USA

I INTRODUCTION

We report the first successful experiments to produce a source (prototype) of polarized electrons using elastic electron-hydrogen spin-exchange collisions together with a teflon-coated hydrogen containment chamber and a longitudinal magnetic trap for electrons. This source is suitable as an injector to a typical linear electron accelerator.[+] A forseen larger device based on the present experience should yield a much larger pulse of highly polarized electrons over a time interval of about one microsecond, repetition rate $0-10^3$ Hz, and possess excellent phase-space properties.

We have also made a rough measurement of the electron-hydrogen total spin-exchange cross-section (5-10 eV), and we report this value.

The underlying technique and experiment was originally proposed in 1965[1,2]. There are two unique features characterizing this source. First, we have potentially a very large interaction space between the electron and hydrogen systems by utilizing a hydrogen maser feature where state-selected hydrogen atoms are mechanically trapped within an enclosure coated with teflon without experiencing appreciable depolarization[3]. Second, electrons are trapped by means of a longitudinal geometry magnetic trap with electrodes[4].This trap geometry, as opposed to a classic quadrupole trap, lends itself to the maximization of the interaction volume while at the same time remaining compatible with the linear accelerator. In addition it leads to a higher intensity not only because the volume is larger but also because the eventual space charge effect limitations are less severe than for an equivalent volume quadrupole

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[+] For a polarized electron source to be compatible with a typical electron linear accelerator (linac), it must satisfy at least the following requirements: pulse length $\simeq 1$ μsec, emittance $\simeq 10$ mrad cm, repetition rate in the 50-60 Hz region or higher, e.g., 360 Hz for SLAC; energy about 50 - 100 KeV.

trap. We refer to reference (5) where some of these ideas and design fundamentals are delineated.

After initial experiments in 1966 on the longitudinal trap[4]) at CEA, (Harvard-MIT), we became aware of an independent proposal[6]) to produce polarized electrons by spin-exchange between a <u>crossed</u> polarized alkali beam in a short classical quadrupole electron trap. The first results using this method were given shortly thereafter[7]. Recently a more systematic study of the source has been published[8].

From the very beginning it was evident to us that we had embarked on the right course from the point of view of maximizing the electron intensity by means of the hydrogen maser "trap" and a longitudinal electron confinement. It appeared that, given other things constant, our technique should yield several orders of magnitude more intensity, and for a variety of reasons would be more compatible with a high energy electron linac. It was evident that the ultimate intensity limitation would be due to electron space charge effects. See ref. (5). The longitudinal trap would give more breathing room in this regard and the large hydrogen gas "target" (rather than a crossed potassium beam) would reduce significantly the spin-exchange relaxation time allowing higher repetition rates. Hydrogen was chosen as the working gas because it was known that state-selected potassium or other alkalis could not be contained with teflon coated walls without serious depolarization. Secondly, the high excitation and ionization potentials of hydrogen allow one to work with higher energy electrons in the trap, thus making problems with stray fields relatively less important and allowing cooler cathode operation for a given current. Finally, hydrogen gas is readily pumpable by any vacuum system; also, H_2 molecules do not interfere with the operation of the source (see below) and will not contaminate the walls of an electron linac.

We were later encouraged to persue these experiments further because

it seemed that the work of Hughes and Raith et al[9] and Baum and Koch[10] based on the photoionization technique appeared to have an intrinsic intensity limit and other technical problems and that our work could eventually have one and possibly two orders of magnitude intensity advantage. The suggestion of Bjorken[11] that high energy polarized electron beams together with polarized proton targets would be very advantageous to do some unusually interesting experiments in the area of deep inelastic electron-proton scattering, further stimulated the pursuit of the construction and experimentation of this source.

In the remaining sections we describe briefly the basic prototype design and experimental arrangement, the experimental results and draw some conclusions.

II PROTOTYPE DESIGN AND EXPERIMENTAL ARRANGEMENT

The prototype source and the rest of the experimental arrangement is essentially a double scattering experiment. It was designed around the previous-ly available solenoid magnets and the spin-exchange chamber (SEC) that were used to test the lonigtudinal geometry electron trap[4]. The double solenoid bore and the length correspond to an inner volume suitable for a scaled-down device, (in contrast to a large device invisioned in ref. (5)). The anticipated electron-hydrogen interaction volume was to be about $1 cm^3$. Fig. 1 shows the experimental arrangement which includes the SEC with electronics, the Stern-Gerlach hydrogen separator magnet (the last experiments made with an additional electromagnet sextupole, see below), and the Mott analyser system composed of a spin-precessor electrostatic spectrometer and scattering chamber. The present system was built primarily to test the design criteria given in ref. (5).

It was decided to try to design a system which would be very close to an operational device (even though a prototype), that is, one that could be

compatible with a linac and give steady operation, rather than an "atomic"

physics experiment. However, it was felt that both the theoretical and experi-

mental basis of this source was sufficiently strong to justify the engineering

of some components which would be immediately compatible with the linac and

continuous operation. As it turned out we have largely succeeded in doing this.

Fig. 2 shows the spin-exchange-chamber and the source proper. The drawing is to

scale although partially schematic.

1) <u>Mott Analyser</u>

The Mott polarization analyzer is a simple system composed of a soft

aluminum scattering chamber and a 90° parallel plate electrostatic spin-

precessor spectrometer which is enclosed in a soft iron vacuum box shield. The

scattering chamber is rotatable 360° around the axis of the incident electrons.

Two surface barrier detectors are mounted at 105° with respect to the axis of

incidence on the targets. This angle was adopted because at this angle the

product of the Sherman function and the scattering cross-section for a gold

nucleus reaches a maximum for electrons in the 50-100 keV region. Further, good

experimental values for the Sherman function are known. On this matter we relied

heavily on the work of Van Klinken[12]). The target holder consists of a cross

arrangement and four gold targets of different thickness can be mounted

simultaneously and brought into target position by remote control. The Mott

analyser system was largely designed by J. Dekleva[13]).

2) <u>Spin-Exchange-Chamber and Source Proper</u>

The spin exchange chamber (SEC) has cylindrical symmetry and is located

inside a 30 mm stainless steel cylinder which is in turn supported in the center

of a cylindrical vacuum envelope of about 60 mm diameter. See Fig. 2.

The SEC assembly is composed of two trapping electrodes placed symmetrically with

respect to the hydrogen entrance port. On the left is a two element electron

gun with an indirectly heated cathode and a two mm diameter anode aperture. The SEC is raised to the accelerating potential (50 - 75 kV), while the vacuum envelope is at ground potential. Outside of the vacuum is a split-coil, air-cooled solenoid magnet producing a magnetic field of up to 1 kG at the electrodes with an approximately 30% dip in the middle. Typical average operating field was about 400 Gauss, however. The magnetic field is not a strong "bottle field", except for some particles of very high pitch. The axial trapping is achieved by means of the two electrodes, E1 (-25v), E2 (-25v), which produce electrostatic potential barriers characterized by very fast axial fall-off, see ref. (5). The radial confinement occurs by means of the magnetic field which also specifies the quantization axis. The field is terminated on the right by a soft-iron plug (at ground potential). The electrons emerge from the SEC, are accelerated to the Mott scattering energy, continue through the aperture of the plug and the transverse magnetic field components, and enter the spin-precessor. While in transit through the transverse magnetic field components they are somewhat depolarized, however, this is a small effect. Fig. 3 indicates the pulse scheme applied on the electrodes and the cathode during filling, containment and ejection.

The base vacuum in the SEC region is in the 10^{-9} Torr range. It is achieved by a silicon fluid (Dow Corning 705) diffusion pump which is carefully trapped, using a Granville-Phillips liquid nitrogen trap. The rest of the system has lower vacuum and is pumped differentially with respect to the SEC.

The elements left of the cathode are mainly wires and high voltage shields that connect electrically, through a high voltage bushing, to the electronics which sit at the accelerating potential. The leading edge of the ejection electrode pulse (E2) is transmitted to ground potential by means of photoelectric diodes and a lens system. It generates a pulse that gates the pulse height analyser, so that only those electrons which are ejected and

scattered by the gold target are recorded, i.e., the counting system is "on" only during an interval of a few microseconds corresponding to the ejection pulse.

The SEC and the two electrodes are made out of soft aluminum and were first coated with teflon in the following manner. One part of TFE-Flourocarbon resin dispersion (60% solids) was mixed with two parts distilled water and 0.05 parts of Triton X-100. This solution was applied on the inner surfaces of the SEC and the electrodes. Thereafter, the pieces were elevated for about 30 minutes to $370^{\circ}C$ in a well ventilated oven. The "water drop" test was used to determine the quality of the coating.

The first trapping studies with teflon were carried out at DESY and were a continuation of the early experiments at CEA, where no teflon was used. It was determined that a very thin and uniformly applied teflon coating yielded good trapping behaviour. However, it was difficult to achieve this high quality coating reproduceably. The implication was that a nonuniform application resulted in non-axially symmetrical electric fields and trapping times were drastically reduced. On the other hand, an application of a spiral scratch on the inner surface of the teflon coated SEC and circular scratches on the inner faces of the electrodes appeared to give good results. For the sake of convenience, efficiency and reproduceability, it was decided to install tiny aluminum rings in the SEC and the electrodes. Four of these rings were installed within the SEC and two each within the electrodes. They assured symmetrical trapping fields. This seemed to give consistantly good trapping behaviour and the experiments were carried out using this technique.

3) Hydrogen State-Selector

     With the exception of the hydrogen discharge source, the first tests

encompassing the whole system were carried out using a state selector similar

 to what is being used in the hydrogen maser set-ups at Harvard. The hydrogen

molecules are dissociated using a microwave cavity operating at 2.45 GHz. The

total power input is about 100 watts. The hydrogen gas flows into a quartz tube

mounted within the cavity, is dissociated and a mixture of molecular and atomic

hydrogen leaks out through a 0.5 mm aperture which is on the symmetry axis of

the permanent magnet sextupole (bought from Varian-Bomac Division). This magnet

and other details are described in reference (14). The two upper hyperfine

states of ground state atomic hydrogen are preferentially selected and continue

to the SEC. Typical state selected fluxes of hydrogen entering the SEC are in the

range of 10^{13} - 5 x 10^{13} atoms per second.

     We recognized that the Varian magnet state-selector system was

inefficient. However, it was sufficient to demonstrate that the source would

produce polarized electrons. An improvement was made by putting in an electro-

magnet sextupole (courtesy of Physikalisches Institut der Universität Bonn,

see reference (10)) following the small permanent magnet sextupole. That is,

the two magnets were installed in series giving a good approximation to an

axially tapered magnetic field which tends to suppress the F = 1, m_F = 0 state

(discussed in ref. (5)). The use of the larger electromagnet made alignment

less critical and gave better focusing properties. This arrangement improved

the state selection efficiency, yielding higher effective hydrogen polarization

within the SEC, and consequently improved the electron polarization.

III EXPERIMENTAL RESULTS

The first detection of polarized electrons using the above prototype arrangement (Varian magnet) was achieved at DESY, Hamburg, late 1972, after equipment transfer from CEA in early 1971[15]). We indicate the following experimental parameters. The interaction volume was about 0.4 cm^3 (the trap was 15 cm long, and the anode diameter 2 mm). This defined the zone where most of the electrons were trapped. The hydrogen was confined within a larger volume (see fig.2) that embraced the trapped electrons. The atomic hydrogen density was about 4×10^8 H/cm^3 and the hydrogen experienced approximately 200 collisions (mean) off the teflon coated inner surface before escaping from the SEC. A comparable molecular hydrogen density was also present, however, this had no deleterious effect, since it is well known H_2 acts as a buffer gas with respect to the electrons and the state-selected hydrogen atoms. The electron content was about 4×10^7 electrons and about 10^7 electrons were ejected from the source. The trapped electrons had a broad energy distribution within 5 - 10 eV. The corresponding electron polarization for these first measurements was about 20% using reference (12) to compute the Sherman asymmetry function and to correct for target thickness effects. The gold target was about 100 $\mu gm/cm^2$. The incident electron energy was about 50 keV. The computed asymmetry function, S, is about 0.2.[+] The electron polarization was further corrected due to imperfect precession in the 90° spin-precessor and due to small depolarization effects at ejection. The latter two effects were less than a few percent.

In fig. (4) we show the first set of data. We attributed the relatively low value of electron polarization to two factors. First, we felt that the state-selector system efficiency,(by system we mean the magnet itself and the

[+] $P = \dfrac{A}{S}$ = electron polarization

rest of the arrangement, i.e., source aperture, alignment, collimators and etc.), was not more than 50%. Further, the effective hydrogen atom polarization within the SEC was even lower due to the fact that in a 460 Gauss field the F=1, $m_F=0$ state was not fully decoupled. In that case, however, the 20% measured figure was still too low. Secondly, it was possible that the difference was due to the depolarization of hydrogen at the small metal surfaces within the SEC and, perhaps, due to imperfect coating of teflon. Tests with new coatings and even further reduction of metal surfaces yielded the same effects. Therefore, it was reasonable to assume, although not conclusively, that the problem might be the state-selector system.

We performed subsequently a carefully controlled experiment, particularly concentrating on the state-selector. The results are shown in Fig. 5. A 30% polarization increase was achieved by introducing a 0.1 cm diameter spherical stop at the exit of the magnet and thus reducing the contamination of non-state selected atoms that go through essentially a field free central region near the axis.

The last set of data shown in Fig. 6 shows considerably improved results using the two magnets in series. A polarization of over 60% is indicated. It appears reasonable to assume that with a very carefully designed state selector magnet and system it would be possible to raise the polarization even further.

Of course it still leaves open the question of hydrogen depolarization within the SEC, deleterious electron depolarization effects during ejection and other possible depolarization mechanisms of both the electrons and hydrogen. However, these effects, for the present experimental conditions, should be not more than 15 - 20%, if not less.

In Table I we indicate the measured and energy averaged total electron-hydrogen spin-exchange cross-section for 5 - 10 eV energy electrons and compare to the theoretical calculations. The largest uncertainty is in estimating the

atomic hydrogen density in the SEC and the mean electron velocity. These
uncertainties reflect the large spread in the estimated experimental value.
The lower limit is a rather firm boundary, however, and the quoted value
supports weakly the variational calculations of Rudge[16]). A more refined value
will be published at a later date.

IV CONCLUSIONS

We have presented the first experimental results of a spin-exchange polarized electron source prototype , which could be used as an injector into a high energy electron linac. At the outset the aim was to design something that would be immediately compatible with a linac and would approximate an operational device. The other simultaneous and of course primary objective was to build a simple scaled-down device in order to test the basic idea of using elastic electron-hydrogen spin-exchange collisions together with a longitudinal electron trap with teflon coatings. It appeared that this combination of factors would have an intensity advantage by allowing a large electron-hydrogen interaction volume and also delaying the onset of space charge effects which will mainly limit the ultimate intensity. The results presented here confirm this. The hope is that a large device could be built which would deliver about 10^{10} - 10^{11} highly polarized electrons/μsec with repetition rates and emittance compatible with a typical electron linac.

Based on the present experience, it looks like this design objective is within reach. Some of these ideas have been discussed in reference (5). We would need the following elements or hardware. First, a SEC, say, two meters long and one cm^2 cross-section, i.e., a total interaction volume of about $200 cm^3$ instead of $0 \cdot 4\ cm^3$ in the present device. In other words, a stretched-out and scaled-up version of Fig. 2. Secondly, a sophisticated state-selector system, consisting of a carefully designed and axially tapered sextupole with a Laval nozzle hydrogen source delivering about 10^{16} state-selected hydrogen atoms. That is, a system which would not only give high state selection efficiency of the $F = 1$, $m_F = 1,0$ states with respect to the $F = 1$, $m_F = -1$; $F = 0$, $m_F = 0$ states, but also preferentially separate out the $F = 1$, $m_F = 1$ state. This would be an advantage from the point of view of optimizing emittance, since a field of, say, 100 Gauss would be sufficient for electron radial confinement,

and also satisfactory from the point of view of having a high effective atomic hydrogen polarization within the SEC. Namely, it would not have to be necessary to have a stronger magnetic field if the state selected hydrogen consisted predominantly of the $F = 1$, $m_F = 1$ state, i.e., no need would exist to decouple the electron-proton spins of the $F = 1$, $m_F = 0$ state if it was mainly absent. The hydrogen polarization and in the limit the electron polarization could approach 90%.

The question of eventual intensity is still somewhat open and depends on space charge limitations during filling and the need to keep the electron energies low. Based on the present overall experience and trial filling tests using a time dependent cathode pulse, an ejected figure of 10^{10} electrons/µsec appears to be achievable. Any further increase in intensity would need the adaption of a more sophisticated filling technique similar to what has been proposed in ref. (5). In any case the projected figures of the future device are higher than those of any other source proposed to date.

V <u>ACKNOWLEDGEMENTS</u>

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Fig. 1   The Overall Experimental Arrangement used in these Prototype
          Polarized Electron Source Studies.

Fig. 2   Polarized Electron Source Proper. It shows the main components true
          to scale. Some details are schematically represented.

Fig. 3   (A) indicates the physical arrangement and (B) the pulse scheme.
          Cathode pulse voltages were typically ⁻10 V or less. Electrode
          voltages about −25 V.

Fig. 4   First set of data is shown indicating counter asymmetry for two
          magnetic field polarities.

Fig. 5   Asymmetry, A, as a function of trapping time for the case of no
          central stop and with a central stop. A significant improvement is
          seen for the case with a stop.

Fig. 6   Asymmetry, A, as a function of trapping time with the two magnet
          state selector. An electron polarization of over 60% is implied.

Table I   The theoretical and measured (energy averaged) total electron-
          hydrogen spin-exchange cross-sections for 5 - 10 eV electrons are
          indicated.
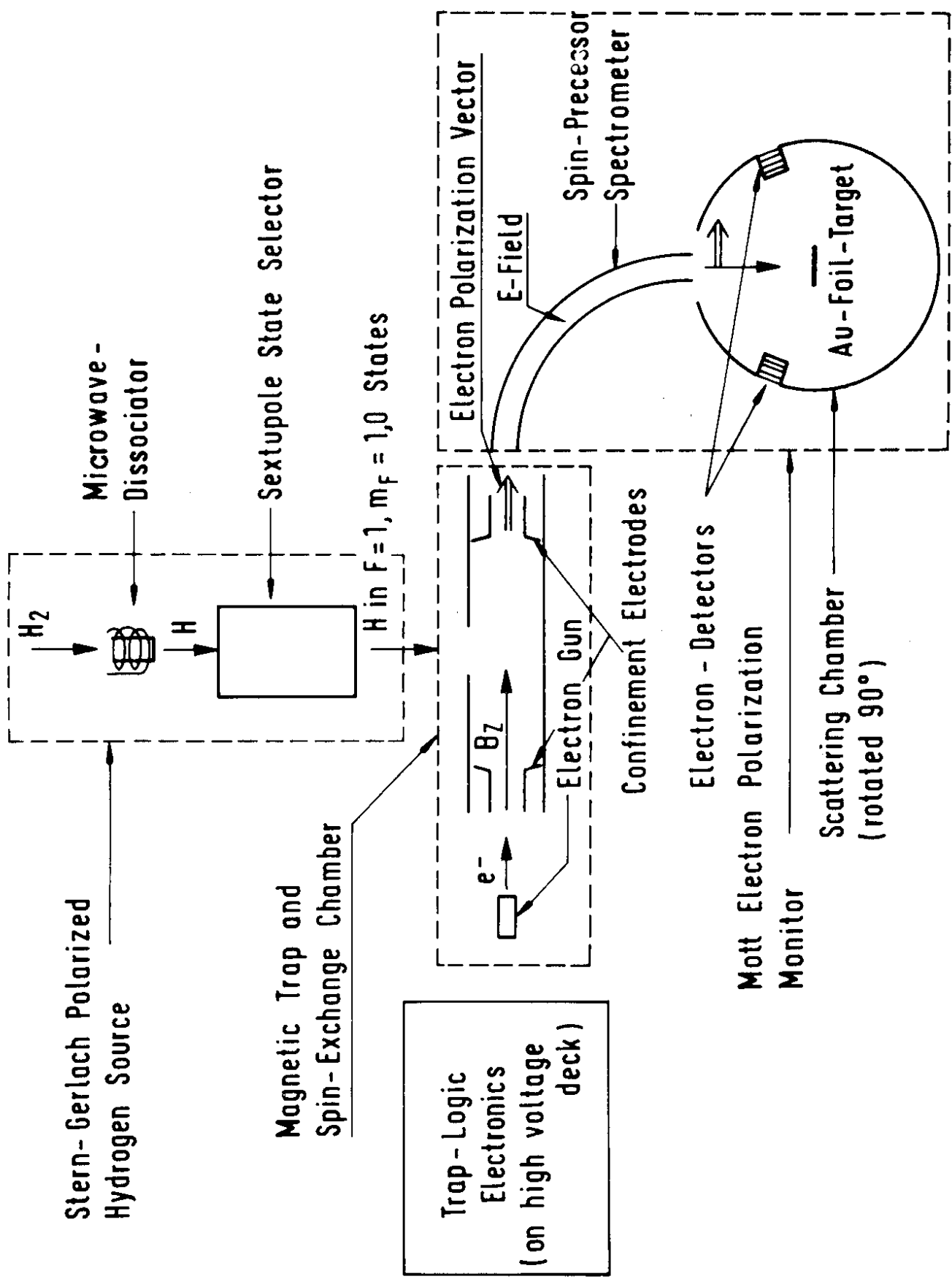
Stern-Gerlach Polarized Hydrogen Source

Microwave-Dissociator

Sextupole State Selector

H in F = 1, m_F = 1,0 States

H_2

H

Magnetic Trap and Spin-Exchange Chamber

Trap-Logic Electronics (on high voltage deck)

e^-

B_Z

Electron Gun

Confinement Electrodes

Electron-Detectors

Mott Electron Polarization Monitor

Scattering Chamber (rotated 90°)

Electron Polarization Vector

E-Field

Spin-Precessor Spectrometer

Au-Foil-Target

POL. ELECTRON SOURCE PROTOTYPE-I

MAIN
VACUUM
PUMP

SOLENOID
MAGNET

H

SPIN-EXCHANGE
CHAMBER (S.E.C.)

TRAPPING ELECTRODES
E1,E2

TWO ELEMENT
ELECTRON GUN

E2

E1

10cm

AT H.V.

LEADS TO ELECTRONICS

(B)

(CONTAINMENT)

~1 µS

FILLING

EXTRACTION

TIME

$-V_C$

$-V_{E1}$

$-V_{E2}$

(A)

E2

E1

H_o

A

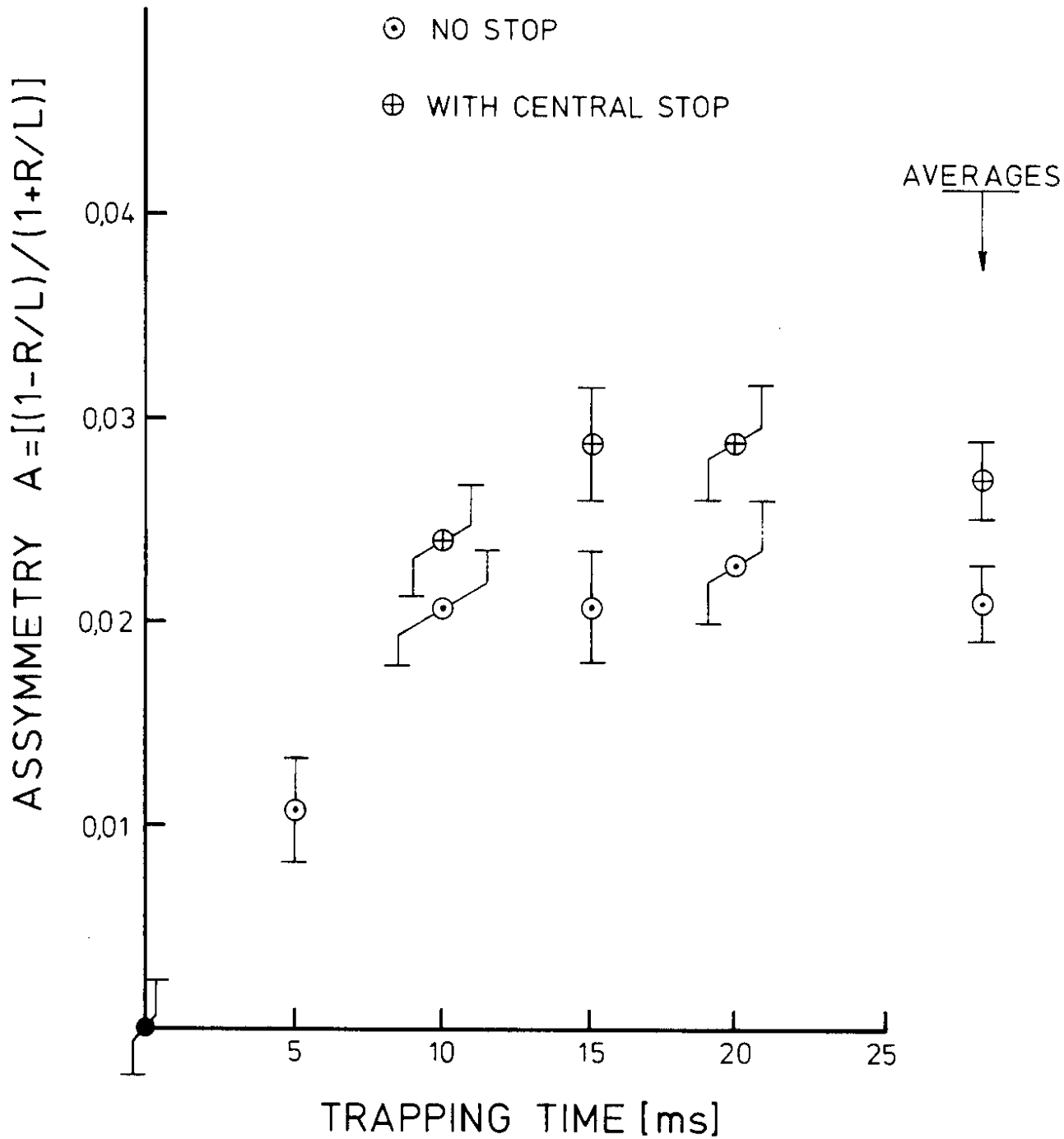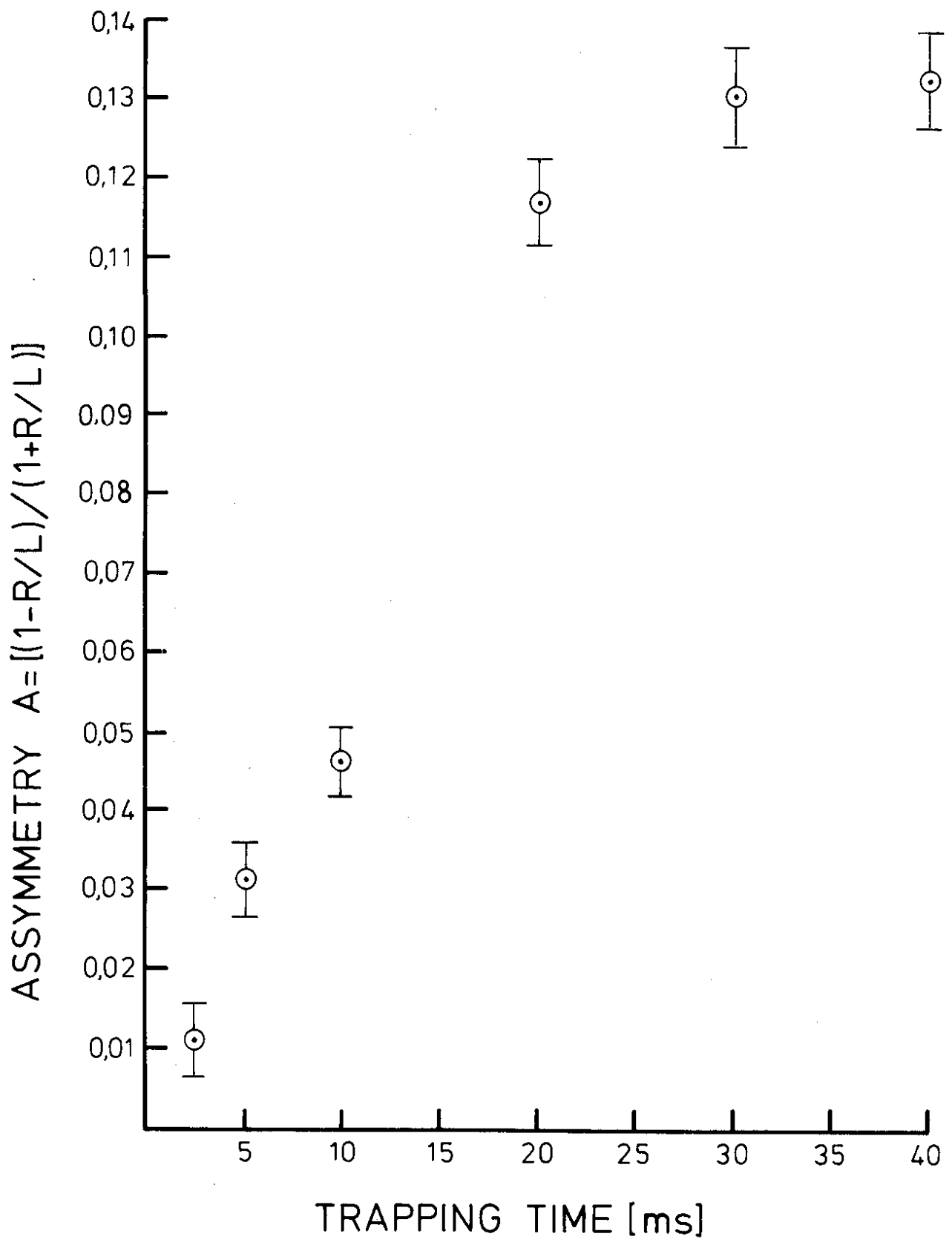C

PULSER V_{E2}

PULSER V_{E1}

PULSER V_C

H.V.
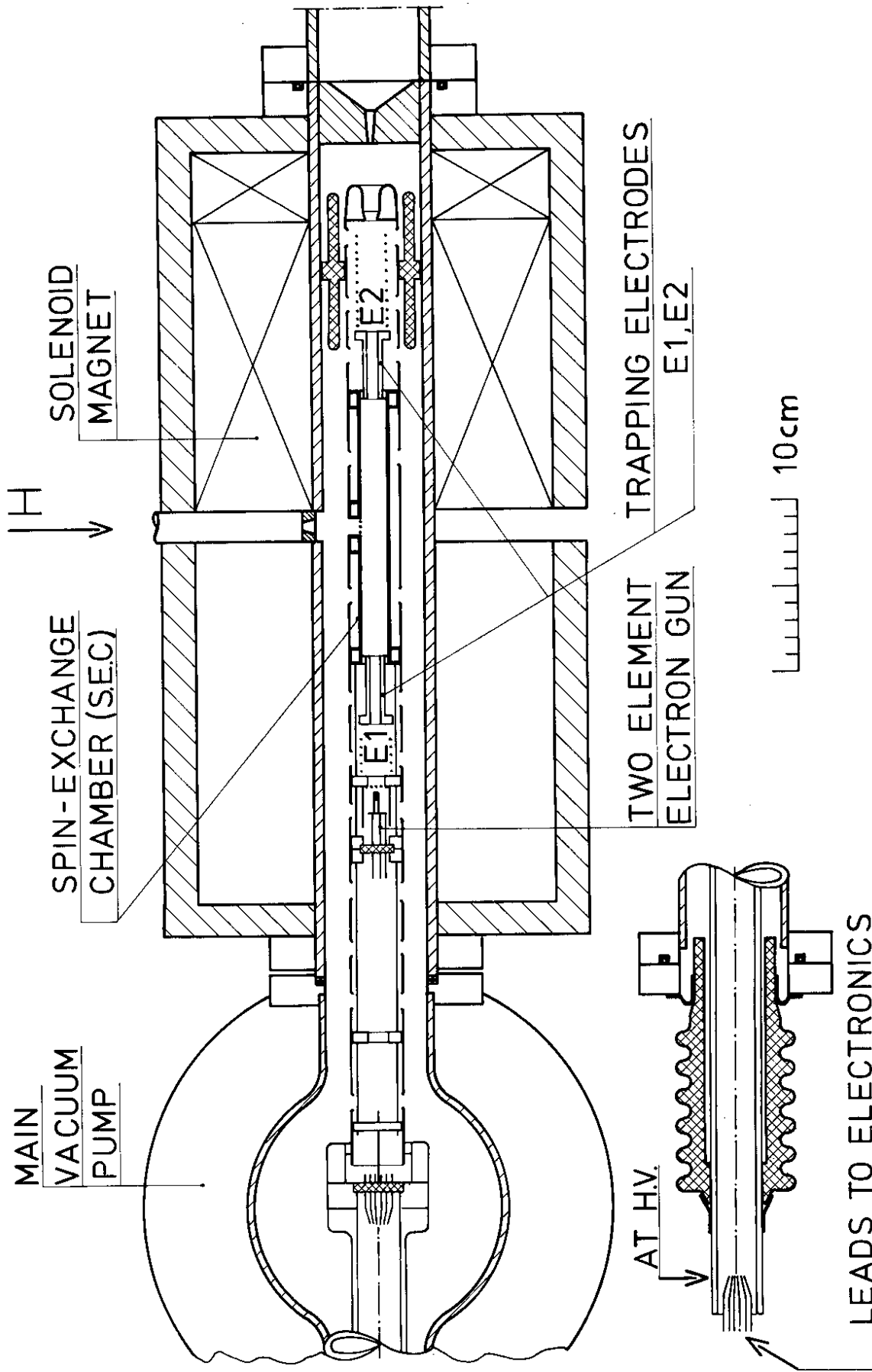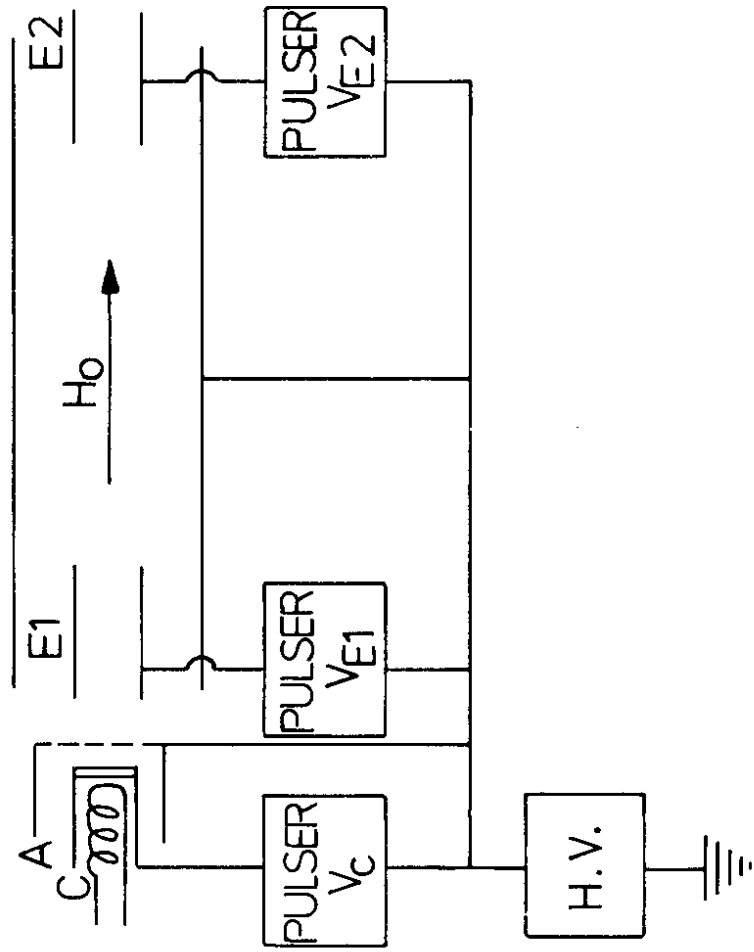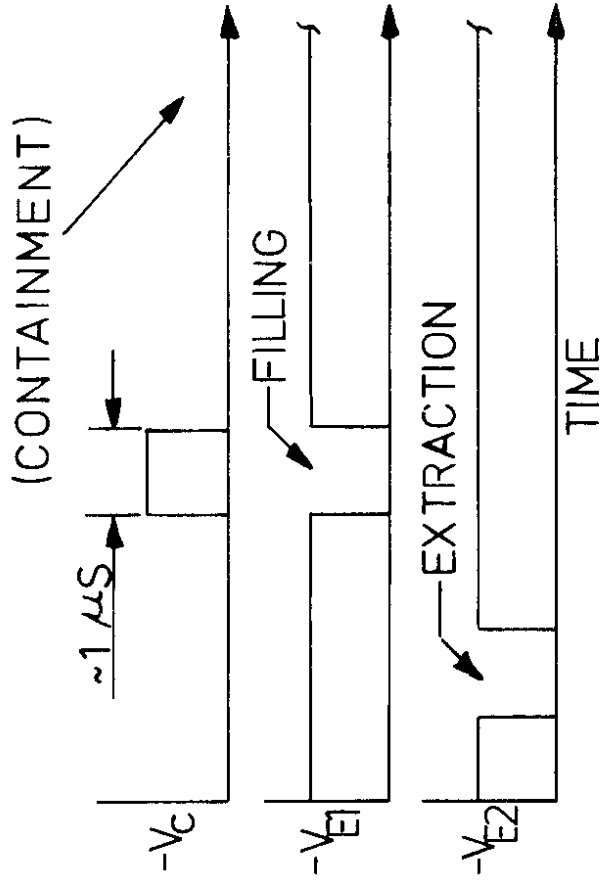
Ratios of Right to Left Counters in the Mott Scattering Apparatus for Two Data Sets with Opposite Magnetic Field Polarities
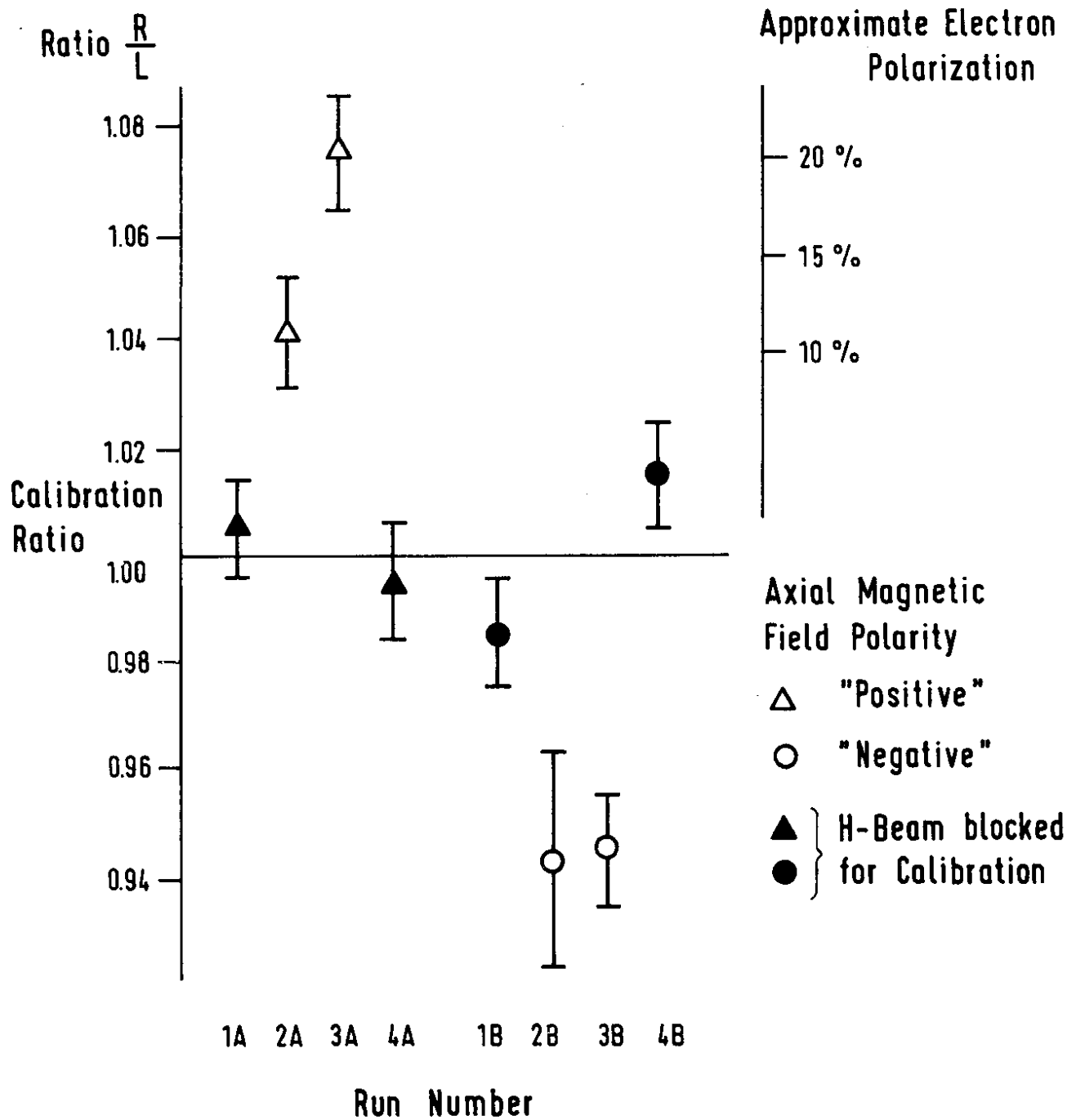
T A B L E   I

Total Electron-Hydrogen Spin-Exchange Cross-section for 5-10 eV Energy

Electrons

σ_{theor} Rudge[16] Variational	σ_{theor} Schwarz[17] Variational	σ_{theor} Burke & Schey[18] 3-state, close-coupling	σ_{exp}
$\simeq 1.0 \times 10^{-15}\,cm^2$	$\simeq 0.6 \times 10^{-15}\,cm^2$	$\simeq 0.6 \times 10^{-15}\,cm^2$	$\gtrsim 0.55 - 1.5 \times 10^{-15}\,cm^2$