A MAGNETIC BOTTLE WITH ELECTRODES FOR TRAPPING LOW ENERGY ELECTRONS

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Introduction

The previously proposed scheme[1,2] for the production of an intense beam of highly polarized electrons requires the capability of trapping very low energy ($\lesssim$10 eV) electrons for periods of $\lesssim$10ms. The electron cloud would be confined in a polarized atomic hydrogen atmosphere within a strong magnetic field that serves to decouple the hyperfine structure interaction of the F=1,m_F=1, m_F=0 states which are previously selected by means of a hexapolar field. The electrons would then spin-exchange with the polarized hydrogen atoms and, given a sufficiently long trapping period, become ~100% polarized. The trapping period, characterized by the spin-exchange relaxation time, depends on the density of the hydrogen and the spin-exchange cross-section.[3] Anticipated spin-exchange cross-sections[3], together with experience as to hydrogen densities obtained in hydrogen maser experiments at Harvard[4], indicate a relaxation time of $\lesssim$ 10 ms. This paper describes a device that provides the required trapping time and is compatible with the rest of the envisaged apparatus. A slightly modified form will allow easy introduction of hydrogen and pulsed operation suitable for an electron accelerator.

General Considerations

It is known that certain crossed electric and magnetic field configurations can act in principle as well-behaved traps for charged particles. For example, crossed fields are used in devices such as magnetrons[5] and Phillips ionization manometers[6]. In our particular application, however, we must work below the ionization potentials of hydrogen and of any residual gases (also, preferably below the excitation potentials); thus there are no ions, and we deal principally with electrons which experience elastic collisions. It appeared possible that a magnetic field of high axial symmetry together with negatively charged electrodes would give a trapping period of the required duration. The magnetic field would give radial confinement, while the z-component of the electric field would give axial confinement. The radial component of electric field would be constant at any given z and r and would merely introduce a drift velocity, $\bar{v} = (\bar{E} \times \bar{B})/B^2$, leading to a stable dynamic equilibrium.

The possibility of using a mirror magnetic field configuration was also considered, but two objections appeared. First, it would be difficult to introduce the electrons into the trapping region (and to extract them from it) which in turn is enclosed in a mechanical trap for the hydrogen atoms*. Second, since it would require large field gradients, there was danger that the polarized hydrogen states would be depopulated by Zeeman-like transitions[4] because the atoms see a time-varying field as they move within the trapping region.

Experimental Set-Up and Operation

The experimental arrangement is shown in figure 1. The electron source consists of two oxide-coated, directly heated, ribbon filaments. They are parallel to each other and are 0.5 mm from a tungsten anode grid. The current through each flows in opposite directions to minimize stray fields. The useful emitting area of each is 0.7x10.0 mm^2.

The solenoidal field has high axial symmetry and is produced by two twin solenoids each capable of carrying two different current densities. Each twin is encased in a magnetic shroud and can be either air cooled or water cooled. Each is about 23.0 cm long and has a 7.0 cm bore. (In the polarization experiment the hydrogen beam will be introduced between the two solenoids, perpendicular to the axis.) The maximum field capability is 10 kG when water cooling is used.

Figure 2 shows the pulsing scheme used in present experiments. If at the end of a trapping period we wish to eject from the trapping region, electrode #3 is

* The objection to having the electron source within the trap is the fact that the hydrogen would get depolarized by collisions with this source.

brought to ground, maintaining electrode #2 negative, and the electrons are collected by the cup*. After a slight delay, #2 is pulsed to ground while #3 is made negative. The cathode is pulsed simultaneously. In this manner a new bunch of electrons is introduced. The repetition rate used is the maximum permitted by the chosen trapping period.

The above capability of pulsing various elements both as a group and individually is very useful in diagnosing the correct operation of the device. Also, since the basis of diagnosis is conservation of charge, the design of the device is such that charge collection can be measured at all elements that can conceivably be "seen" by the electrons in the system. For example during the trapping mode (fig.2), charge can be collected both at the cup and at the surrounding cylinder. It is found that even for the longest trapping period (20 ms) the charge collected at the cylinder is three orders of magnitude smaller than that collected at the cup and increases only very slightly in the range of 0.1 ms to 20 ms.

Figure 3 shows a typical set of data summarizing the performance of our device in the present form. We have plotted the ratio of collected charge (by the cup) in the trapping mode to that in the free running mode (#1 and #2 being pulsed; #3 at ground), I_t/I_f, versus the trapping period for two choices of B_{max} (B_{max} is defined in fig. 1). Note that in the range of trapping periods 0.1 ms to 2.0 ms, I_t/I_f is nearly constant and is independent of B_{max}. For trapping periods greater than 2.0 ms, I_t/I_f appears to become field dependent. We interpret this as follows. The electrons experience elastic collisions with the residual gas (no atomic hydrogen was used in these experiments) and undergo a change in phase space with a transfer of some of their kinetic energy from the parallel to the perpendicular mode.

By 2.0 ms they have experienced on the average 5 to 10 collisions, but without having acquired sufficient radial velocity and cyclotron radius so that the #3 grid will interfere with their exit from the trap. As we go to longer trapping periods this is no longer true and the electrons that have acquired sufficiently large v_r are intercepted by the grid. Increasing the field from 235 gauss to 1200 gauss improves their transmission. We find this argument entirely consistent with the dimensions of the grid and with tests of transmission through a single grid which provide an indication of the effective transmission of the grid (relative to the "optical" transmission). Figure 4 illustrates in more detail the behavior of I_t/I_f as a function of B_{max} and pressure.

It appears that for trapping periods in the range of 0.1 to 20.0 ms and assuming other parameters as indicated in fig. 3 our bottle stores electrons efficiently, i.e., the fraction of the electrons lost is negligible.

The charge density achieved during trapping is $0.5\text{-}1.0 \times 10^7$ electrons/cm^3, and extension of the tests to longer periods if desired requires larger initial currents and trapping volumes to make detection reliable and to avoid space charge effects.

Conclusion

These experiments have demonstrated the capability of trapping low energy electrons for the required period in order for them to be polarized through spin-exchange collisions with polarized hydrogen atoms. Any instabilities that do exist appear to be slow in comparison to the trapping periods. Space charge limitations may become important in the 10^8 to 10^9 electrons/cm^3 range where space charge potentials become comparable to ionization potentials. These possible space charge limitations could be overcome by going to larger trapping volumes if so desired from the standpoint of maximizing the net intensity of polarized electrons.

* Electrodes #2, #3 and the anode consist of 100 line /inch mesh of 0.001 inch tungsten.

References

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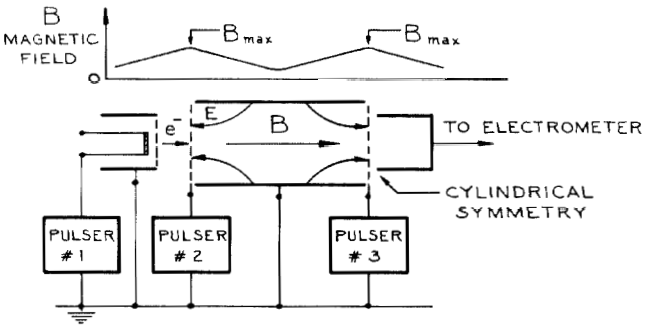

Fig. 1. The experimental arrangement.

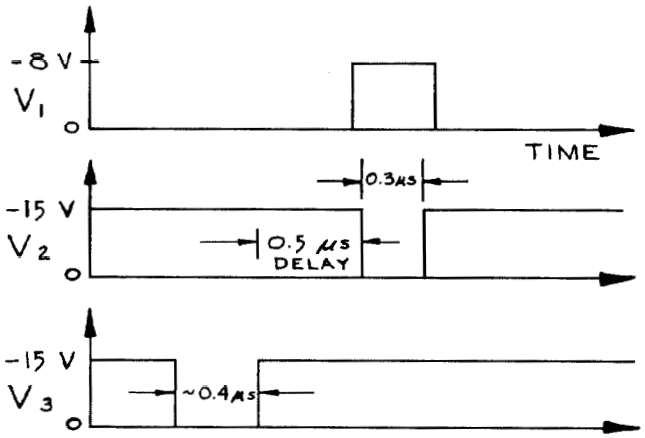

Fig. 2. Pulsing Scheme during trapping mode.

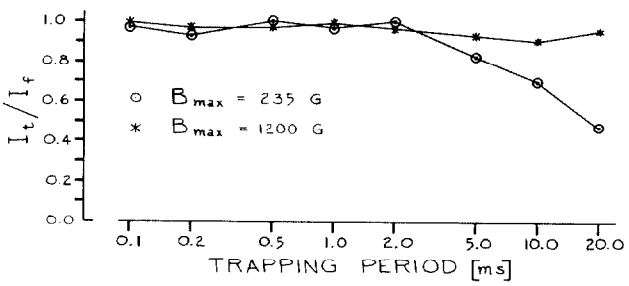

Fig. 3. The ratio of collected charge in trapping mode to collected charge in free running mode (#1 and #2 pulsed; #3 at ground), I_t/I_f, as a function of trapping period. The curve is normalized to I_t/I_f at 0.1 ms. Pressure is approx. 0.6 x 10^{-6} torr.

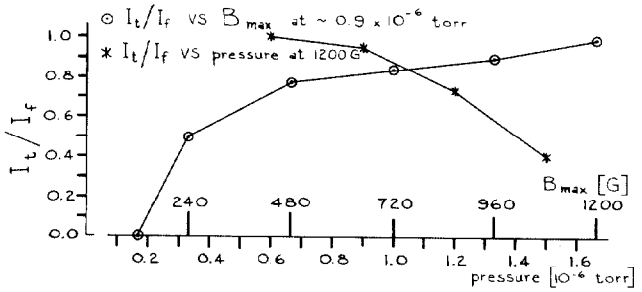

Fig. 4. I_t/I_f versus B_{max} and pressure. The trapping period is 10 ms.