ACCUMULATION AND BUNCHING OF POSITRONS

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ABSTRACT

Results from a positron accumulator that operates efficiently over a range of repetition rates from 100 to 1000 Hz are presented. Moderated β-decay positrons from a radioactive source are accumulated in a Penning-style trap. At a repetition rate of 250 Hz an accumulation efficiency of $\sim$ 25% has been achieved. Two techniques for reducing the time spread of the positron pulses have been investigated. The most successful method reduces the pulse width from 120 ns to 20 ns.

INTRODUCTION

In many of the experiments that involve positrons it is advantageous to use a pulsed positron beam. Such a beam can provide slow, time-tagged positrons for measuring decay rates, for example of positronium (Ps),[1] or positrons in matter.[2] A source of pulsed positrons could furnish high positron densities for antihydrogen-formation experiments.[3] A pulsed positron beam is also invaluable in experiments that employ other pulsed particle or laser beams. In an experiment in progress at the University of Michigan[4] a pulsed laser is required to measure the fine structure intervals $2^3S_1 \rightarrow 2^3P_J$ (J = 0,1,2) in Ps. The necessity of using an intense pulsed positron beam which is synchronous with this laser motivated the work presented in this paper.

A common source of pulsed positrons is bremsstrahlung pair production from pulsed relativistic electrons. This method produces intense microsecond-long positron pulses that need to be further time-compressed to be useful for many experiments.[2,5] The cost of constructing and operating these pulsed positron sources is quite high.

A more economical beam of pulsed positrons can be provided by accumulating positrons from a radioactive source. Several mechanisms for trapping moderated positrons have been investigated. An rf cavity tuned to the positron cyclotron resonance frequency has been used to provide accumulation by increasing the transverse energy spread of the positrons.[6] A harmonic bunching technique subsequently decreases the time spread of the positron pulses. The minimum repetition rate for efficient accumulation in this apparatus is greater than 1 kHz, which is high for most of the experiments mentioned above. Another technique to accumulate positrons is based upon the use of inelastic collisions with neutral gas molecules[7] to cool the positrons. This design requires extensive differential pumping and the optimum repetition rate is much lower than 100 Hz. The design for an accumulator which operates efficiently at moderate repetition rates (100–1000 Hz) has been tested at the University of Michigan. The work presented here marks a significant improvement over the preliminary results reported previously.[8]

ACCUMULATION

The design of the accumulator is based on a cylindrical open-endcap Penning trap.[10] The electrostatic lensing elements and the applied electric potentials are shown schematically in fig. 1. Beta-decay positrons from a 3-mm diameter, 15-mCi ^{22}Na source (S) are moderated using a tungsten-vane moderator (M) in a Venetian-blind geometry.[9] The trap is divided into 13 cylindrical sections (T_1–T_{13}) which are $\sim$ 5.1 cm in diameter and $\sim$ 5.5 cm long. The gate (G) is a high-transmission grid placed at the opposite end of the trap. Radial confinement is provided by a solenoidal magnetic field of 90 G and the effects of the Earth's magnetic field are cancelled using a pair of Helmholtz coils.

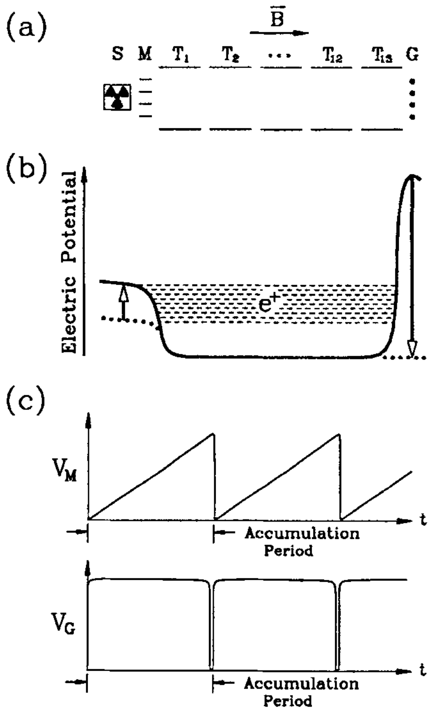

Fig. 1. The electrostatic lensing elements of the accumulator are schematically shown in (a). The electric potential applied to the radioactive source, moderator, sections of the trap, and the gate are denoted by V_S, V_M, V_{T_i}, and V_G respectively. These potentials are shown directly below in (b). The arrows indicate voltages which are changing in time. The time dependence of V_M and V_G are explicitly shown in (c). V_S is always $\sim$ 3 V higher than V_M.

Slow positrons are emitted into the trap with a moderation efficiency of approximately 2×10^{-4}. The kinetic energy of these positrons in the trap is given by

$$E_K = e\Big(V_M(t)-V_{T_i}\Big)-\phi_+ \qquad (1)$$

where e is the positron charge, $\phi_+ \simeq -2.8$ eV is the work function of the tungsten moderator, and V_M and V_{T_i} are defined in fig. 1.

A high positive potential is applied to the gate during accumulation. Slow positrons are reflected from this potential back toward the moderator. The time required for positrons to travel from the moderator to the gate and back is called the trap period and is a function of E_K. During the accumulation period (see fig. 1c) V_S and V_M are continuously rising at a rate denoted by R_{inc}. If these potentials increase by more than $|\phi_+/e| \simeq 2.8$ V during one trap period, the returning positrons will not be energetic enough to reach the moderator. Thus, these positrons become axially trapped between the moderator and the gate.

However, it is possible to accumulate positrons efficiently ($10-45\%$) even when V_M increases by $<$ 100 mV during a trap period rather than 2.8 V. Several possible explanations for this were investigated. Processes such as neutral gas scattering, positive ion scattering, and electron cooling were ruled out. The observed high accumulation efficiency is the result of magnetron motion as discussed below.

MAGNETRON MOTION

In order to accumulate efficiently, it is necessary to prevent the positrons returning toward the moderator from striking the vanes. If moderated positrons strike the tungsten vanes, they may be remoderated and reenter the trap. However, even with a remoderation efficiency of $\sim$ 20%[11] less than 1% of these positrons will survive after three trap periods. Magnetron motion aids accumulation by preventing positrons from hitting the moderator vanes. Positrons undergo an $\vec{E} \times \vec{B}$ drift—the magnetron motion—while reflecting from the electric potential of the gate. The drift velocity is given by

$$\vec{v}_d = \frac{\vec{E} \times \vec{B}}{B^2}. \quad (2)$$

The details of the magnetron motion depend upon the ultimate proximity of positrons to the gate compared to its grid-wire spacing. If the field near the gate is strong enough that positrons only approach to within a few times the grid-wire spacing, then the gate's grid structure is of no consequence. Hence, the positrons remain within a region in which the electric field has only axial and radial components and, as a result, the drift velocity has only an azimuthal component. The projection of the resultant azimuthal displacement on a plane perpendicular to the magnetic field is a section of a circle centered on the cylindrical symmetry axis of the electric field lines. In this case positrons which are farther away from this symmetry axis are displaced more than those near the center because they sample a larger radial electric field.

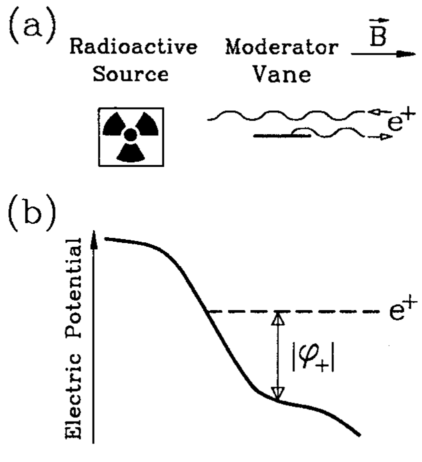

Fig. 2. A schematic illustrating the effect of magnetron motion is shown in (a). The cyclotron orbit of a positron is shown both before and after magnetron motion occurs. The returning positron does not strike the vane from which it was emitted and is therefore reflected back into the trap by V_S. The relevant electric potentials and the corresponding positron energy are directly below in (b).

On the other hand, if the field near the gate is weak enough for positrons to approach to within a grid-wire spacing, then the positrons will sample a region of the electric field that is strongly influenced by the grid structure. In this case, though $|\vec{E}|$ is relatively small, the positrons sample an electric field which has components in all directions. Therefore, magnetron motion occurs in both the azimuthal *and* radial directions. This displacement does not depend upon the gross cylindrical symmetry of the field and hence may strongly effect positrons irregardless of their distance from the symmetry axis.

In either case the displacement caused by the magnetron motion can aid accumulation. Due to the magnetron motion positrons returning to the vicinity of the moderator may fail to strike a vane. Such positrons are reflected by V_S and reenter the trap (see fig. 2). Thus, the increase in V_S and V_M required for accumulation ($|\phi_+/e|$) may be applied over many trap periods.

ANALYSIS AND RESULTS

A channel electron multiplier array (CEMA) assembly is placed after the gate. This assembly includes a phosphor screen to observe the beam profile. A 5 cm × 5 cm plastic scintillator is placed outside the vacuum chamber to detect γ rays from the annihilation of positrons on the channel plate. In order to calibrate these detectors and optimize the positron optics, the accumulator was operated in a continuous mode in which V_G was held below V_M. Coincidences between the signals from the CEMA and the γ-ray detector can be used to calculate the slow positron beam rate (B) as well as the efficiencies of the CEMA (η_β) and the γ-ray detector (η_γ) as follows:

$$B = \frac{R_\beta \, R_\gamma}{R_{coinc}} \quad , \quad \eta_\beta = \frac{R_{coinc}}{R_\gamma} \quad , \quad \eta_\gamma = \frac{R_{coinc}}{R_\beta}. \tag{4}$$

In the above equations R_β, R_γ, and R_{coinc} denote the background-corrected CEMA, γ and coincidence rates respectively.

The signal from the CEMA cannot be used to detect pulsed positrons because of noise induced by the high-voltage gate pulse. The pulsed positrons are therefore only detected using the γ-ray detector. A time spectrum of the positron pulse is obtained by collecting coincidences between the gate pulse and γ-detector signal. It is important to note that the use of a γ-ray detector guarantees that the observed signal is unambiguously due to positrons.

The accumulation efficiency is defined as

$$\eta_{acc} = \frac{\text{Number of pulsed positrons per second}}{\text{Slow positron beam rate}}. \tag{3}$$

This efficiency strongly depends on the effectiveness of the magnetron motion in initially trapping the positrons. The magnetron motion, in turn, has a complicated dependence on V_M, $V_{T_{13}}$ and the voltage applied to the gate during accumulation (V_G^{max}). The accumulation efficiency can be improved by increasing the difference between V_G^{max} and $V_{T_{13}}$ since this increases the radial electric field that causes the magnetron motion. The difference between V_M and $V_{T_{13}}$ determines the speed of positrons near the gate and hence the period of time during which magnetron motion occurs (see eq. 1). On the other hand, the difference between V_G^{max} and V_M determines the ultimate proximity of positrons to the gate which in turn determines the nature of the magnetron motion. Furthermore, V_M is not held constant during the accumulation period and, as a result, the trapping efficiency is a function of time. It is the combined effect of this time-dependent trapping probability and the ability of the rising moderator voltage to accumulate the positrons after several trap periods that determines the total accumulation efficiency.

The accumulation efficiency is plotted versus $V_G^{max} - V_M^{min}$ and $V_{T_{13}} - V_M^{min}$ for three different values R_{inc} in fig. 3. For the sets of data plotted in fig. 3a, both R_{inc} and $V_{T_{13}}$ are held constant while V_G^{max} is varied. Therefore it is V_G^{max} that determines the nature of the magnetron motion. When $V_G^{max} \sim V_M$ the effect of the gate's grid structure on the electric field is the dominant factor determining the trapping efficiency. The smaller the difference between

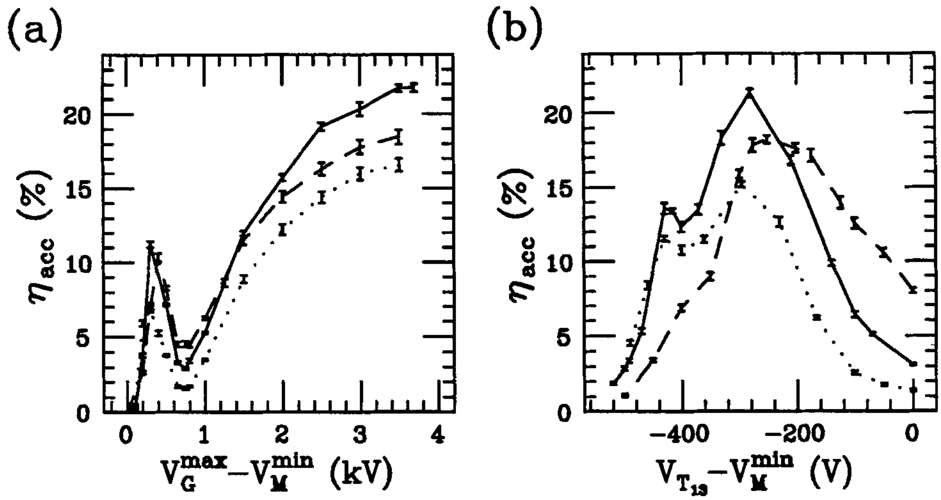

Fig. 3. The accumulation efficiency at a repetition rate of 250 Hz was measured for three different rates of moderator voltage increase. Trap sections $T_1 - T_{12}$ are held at 0 V and $V_M^{min} = 0$ V. The data points are connected with straight lines to be distinguished from one another. Dotted lines are used for the moderator voltage increasing at a rate of $R_{inc} = 37.5$ V/ms, solid lines for the optimum rate of $R_{inc} = 60$ V/ms and dashed lines for $R_{inc} = 90$ V/ms. The effect of V_G^{max} on the accumulation efficiency is shown in (a) where $V_{T_{13}} = -280$ V. The effect of $V_{T_{13}}$ for $V_G^{max} = 3.5$ kV is shown in (b).

V_G^{max} and V_M, the closer positrons come to the gate. These positrons sample an electric field which has greater azimuthal and radial components and therefore higher trapping efficiencies are possible. Consequently for the cases in which positrons are allowed to approach the gate to within a grid-wire spacing the accumulation efficiency is optimized for $V_G^{max} \sim V_M^{max}$ (see fig. 3a). As V_G^{max} is raised above V_M^{max}, positrons do not approach the gate as closely and, thus, the effect of the magnetron motion is reduced and the accumulation efficiency decreases sharply. However, when the voltage on the gate is raised even further, the overall radial component of the electric field becomes large enough to cause a substantial azimuthal drift velocity (see eq. 2) and the trapping efficiency increases. The data in fig. 3b are taken with the same rates of moderator voltage increase as in fig. 3a, but in this case V_G^{max} is held constant while $V_{T_{13}}$ is varied. Increasing $|V_{T_{13}}|$ increases the radial electric field component that causes the magnetron motion. However, this also increases the speed of positrons reflecting from the gate potential and thus decreases the amount of time positrons undergo magnetron motion. These two factors affect the trapping efficiency in opposite directions and lead to the broad maxima seen in fig. 3b. The optimum values for R_{inc} and $V_{T_{13}}$ can be experimentally determined for different repetition rates as demonstrated in fig. 3 for 250 Hz.

The accumulation efficiency could potentially be improved by increasing the pressure of the system. Inelastic collisions with neutral gas molecules can lead to accumulation by cooling the positrons.[7] Elastic scattering from positive ions or neutral molecules can also help accumulation if the scattering angle is sufficiently large. Such large-angle scatterings transfer part of the axial momentum of positrons into cyclotron motion. Positrons become trapped when their axial momentum is insufficient to reach the moderator. However, increasing the pressure also increases the probability of forming Ps. It was found experimentally that an increase in pressure leads to a decrease in the accumulation efficiency which indicates that Ps formation has a larger effect than the gain mechanisms described above.

The positron accumulator described in this paper was optimized to match a pulsed laser with a maximum repetition rate of 250 Hz. The highest accumulation efficiency achieved at 250 Hz is ~ 25%. The parameters which yielded this efficiency and the resultant positron pulse time spectrum are shown in fig. 4.

The accumulator has also been tested at other repetition rates and reasonable accumulation efficiencies were achieved even though all parameters were not optimized. An accumulation efficiency of ~ 45% was obtained at 670 Hz. This result and tests done at 1000 Hz indicate that achieving an accumulation efficiency of ~ 50% at 1000 Hz is quite feasible. The best efficiency achieved at 100 Hz is ~ 10%. The accumulation efficiency is generally lower at low repetition rates because positrons have a finite lifetime in the trap. Positronium formation is the most important factor limiting the efficiency for long accumulation periods.

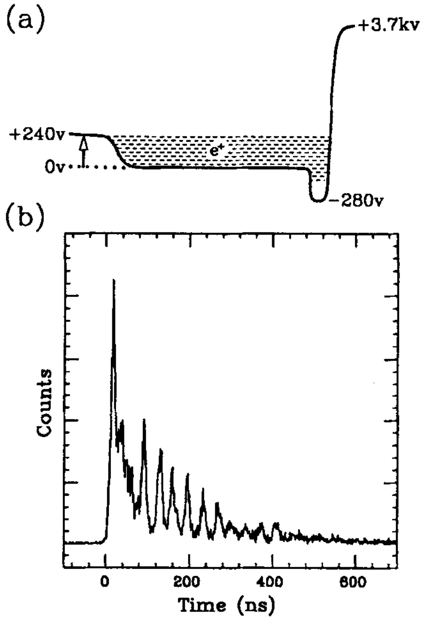

Fig. 4. The electric potential of the lensing elements leading to the highest accumulation efficiency at 250 Hz is schematically shown in (a). The positron pulse time spectrum is shown in (b). The pressure is $\sim 2\times10^{-8}$ torr. The moderator voltage is raised from 0 V to 240 V during the 4-ms period. The accumulation efficiency is ~ 23% resulting in ~ 8 e^+/pulse per mCi of radioactivity.

The initial sharp peak in the time spectrum (see fig. 4b) is due to positrons localized in the small potential well next to the gate (see fig. 4a). The well is generated by applying a higher voltage to T_1 through T_{12} than to T_{13}. This potential configuration increases the trap period (see eq. 1) without changing the trapping efficiency (which depends on $V_{T_{13}}$ as illustrated by fig. 3). The result is a higher accumulation efficiency because positrons return fewer times to the moderator and therefore are less likely to strike a vane and be lost.

The other peaks in the time spectrum are not due to an effect inherent in the accumulation process. Noise induced on the trap sections by the high-voltage gate pulse modulates the positron beam leading to the peaks observed in figs. 4 , 5, and 6. This noise has since been greatly reduced and the peaks mentioned above have smoothed out. These peaks have since been eliminated by placing a ground braid around the gate pulse line and diminishing ground loops.

During accumulation the moderator voltage is raised by 240 V and therefore the energy spread of the pulsed positrons is ~ 240 eV (see eq. 1). This energy spread is small enough that a remoderation efficiency as high as 20% can be achieved[11] if thermal positrons are required. However, for the present application remoderation will not be necessary. The formation probability for n=2 Ps decreases with increasing positron energy but is reasonably constant from 10 to 150 eV.[12] Therefore, the energy spread is not a concern in the fine structure measurement cited above.

COMPRESSION AND BUNCHING

The typical width of the positron pulses (see fig. 4b) is ~ 120 ns (FWHM) which is too large for many applications. Two techniques of time compressing these pulses were investigated. One of these techniques relies on decreasing the physical volume in which the positrons are trapped after accumulation has been completed. This is done by raising the voltage of the trap sections sequentially starting with V_{T_1} (fig. 5). The resulting potential gradient compresses the positrons into an ever smaller volume next to the gate before it is lowered.

During this process positrons within the section which is rising in potential may gain a considerable amount of energy. This not only increases the energy spread of the positrons (which is undesirable for many experiments) but it can also result in detrapping. An effort was made to minimize this energy gain by raising the potentials of the sections slowly and by raising the voltage of one section at a time. Even when the trap sections were raised with a 10-90% rise time of 100 ns and an 80 ns delay between consecutive sections, the accumulated positrons were able to gain enough energy to leave the trap before the gate was lowered. Some of these positrons were even observed to have gained enough energy to exit the trap over the 3.7 kV barrier of the gate. As a result, this method of time compression continuously decreases the total number of positrons in the trap. The best results are therefore obtained if the gate potential is lowered before the compression process has been completed.

The most successful time compression technique is similar to the method of harmonic bunching.[5,6] At the end of the accumulation period a linearly-sloped electric potential is suddenly applied to the trap (fig. 6). This produces a constant axial electric field pointing toward the gate. Positrons which are closer to the moderator are accelerated by the resultant force for a longer period of time and hence leave the trap with a greater speed. The accelerated positrons therefore reach their intended target in less time which can reduce the positron pulse time spread. The farther away from the gate the target is, the smaller the required slope to achieve a given pulse width. Bunching the positron pulse in fig. 4 with a linear slope of 6.6 V/cm and a rise time of 30 ns (10 – 90%) results in a pulse with a ~ 20 ns FWHM as shown in fig. 6.

Using the linear buncher to time compress the pulse also increases the energy spread of the positrons. The energy spread of the bunched positrons was measured by varying the amplitude of the pulse on the gate. Plotting the number of accumulated positrons which were allowed to exit the trap vs. the minimum voltage on the gate results in an S-shaped curve. The 10–90% rise of this curve is a measure of the axial momentum of the accumulated positrons. For the pulse in fig. 6 the energy spread was measured to be ~ 400 eV.

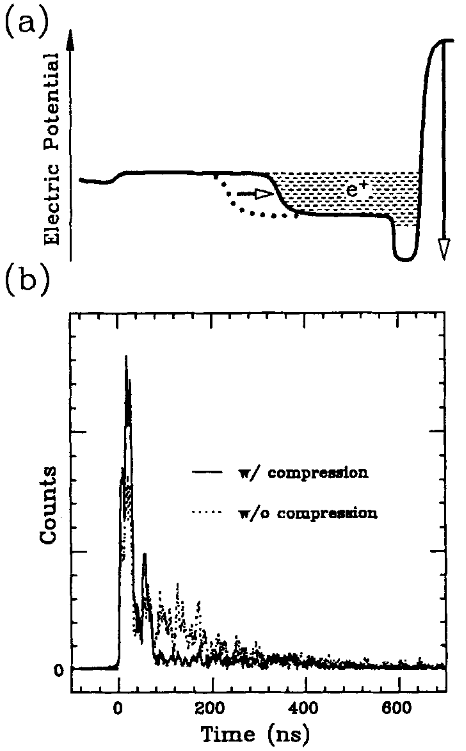

Fig. 5. The electric potential applied to the lensing elements during compression are schematically shown in (a). The time compression achieved on the positron pulse in fig. 4b by raising the sections 300 V in a 10-90% rise time of 100 ns is shown in (b). Consecutive trap sections were raised with an 80-ns delay and the gate was lowered when 9 of the sections were raised.

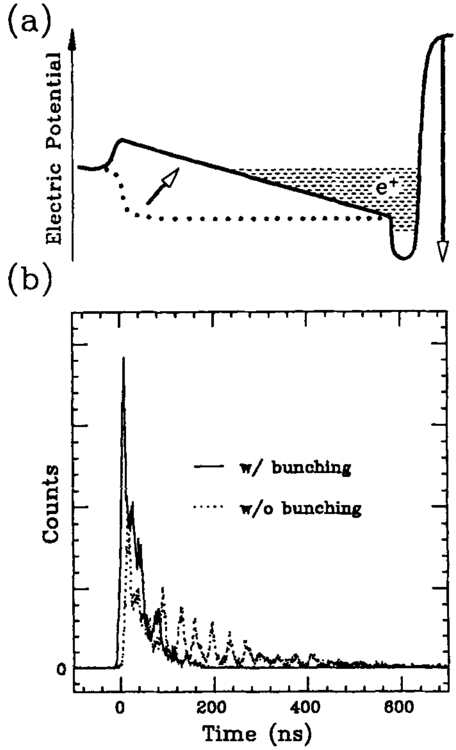

Fig. 6. The electric potentials applied to the lensing elements before and after bunching are schematically shown in (a). The time-compression achieved on the positron pulse in fig. 4b with a potential slope of 6.6 V/cm over the 71-cm trap is shown in (b). The electric potential on the gate was lowered 70 ns after the sloped potential was applied.

Many of the experiments that would benefit from having a pulsed positron beam must be done in a region which is free of magnetic fields. In the present system extraction of the pulsed positrons from the magnetic field is complicated by their relatively large energy spread. The details of extraction depend on the particular system used and consequently will not be discussed here. It is worth mentioning, however, that the bunched positrons shown in fig. 6b have been extracted to a region where the magnetic field is ~ 1–2 G. An extraction efficiency of ~ 60% has been achieved and the time spread of the pulse was increased by only ~ 15%.

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