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Feasibility Study Into the Use of Mechanical Choppers to Alter the Natural Time Structure of the APS

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Introduction

The prospect of extending static x-ray measurements into the time domain is an exciting one indeed. The foundations for this extension have already been laid by some very innovative experiments[(1)] performed at existing storage ring sources. The enormous enhancement in brilliance that the APS will afford over existing sources will, I believe, foster a tremendous growth in the area of time-resolved x-ray experimentation. The growing interest in this field is evidenced by both the number of participants and their enthusiasm at an APS Workshop on Time-Resolved Studies and Ultrafast Detectors[(2)] held on January 25-26, 1988, at Argonne.

In a very general way, one can divide time-resolved experiments into two broad classes: (1) those that take advantage of techniques that permit data to be collected in a more rapid fashion and (2) those that take advantage of the natural time-structure or modulation of the radiation produced by storage ring sources. It is with the latter group of experiments that this report is primarily concerned. Researchers planning to use the time structure are considering both experiments that can be cyclically pumped and probed (which effectively utilize the high repetition rates of synchrotron sources) and one-shot experiments (where the temporal resolution will be commensurate with that of the bunch duration itself, i.e. 100 psec). The natural time-structure of the storage ring may not, unfortunately, be optimal for all time-resolved

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experiments. For example, there has been considerable interest in the crystallography community over the possibility of collecting a Laue diffraction pattern from a single (or several) bunch(es) of x-rays. Integrating detectors (such as film or the new phosphor storage plates) will be needed for these experiments because of their virtually unlimited count-rate capabilities. However, these detectors cannot be electronically gated and therefore the x-ray beam itself must be rapidly shuttered when the exposure is complete. For this type of one-shot experiment a short burst of x-rays followed by a period of darkness long enough to shutter the beam is required. Alternatively, other experiments may need a (user variable) repetitive pulse structure to match the repetition rate of some external pump such as a laser. The problem is then one of how to satisfy those users who require different time structures than that of the normal storage ring operating condition while minimizing the impact on other users. The major thrust of this note is to try to point out some possible solutions to this problem; in particular we will look to see whether the temporal properties of the emitted radiation can be suitably modified through the use of mechanical choppers. It is my intent that this note be somewhat speculative in nature with the hope that it may stimulate ideas in those who read it.

Before discussing the chopper characteristics, it is instructive to review the temporal properties of the APS.

APS Temporal Properties

With a radio frequency accelerating system operating at 353 MHz and storage ring circumference of 1060 meters, the APS will have a harmonic number of 1248; that is there are 1248 equally spaced stable orbital positions or RF buckets around the ring. The explicit timing properties of the ring will depend on which and how many of the RF buckets are filled. Calculations indicate that single bunch instabilities will limit the maximum current per bunch to be 5 milliamps. Hence, to attain a stored current of 100 milliamps a minimum of 20 bunches will be required. If the bunches are equally spaced, this would correspond to an interbunch period of approximately 177 nanoseconds. The calculated bunch durations for low current (<0.5 mA) and maximum current (5 mA) operations are 38.7 picoseconds (2 x RMS) and 116 picoseconds (2 x RMS) respectively. A comparison of the temporal properties of the APS and other x-ray storage ring sources is given in Table I.

Table I Time Structure of Various Storage Rings

	SSRL	CHESS	NSLS	APS
Ec(kev)	4.7	8.7	5.0	19.5
Orbital period (nanoseconds)	760	2560	568	3536
No. of Bunches*	1 (4)	7	30	20 (60)
Bunch Duration (picoseconds)	300	160	1700	116
Interpulse Period* (nanoseconds)	760 (190)	366	18.9	177 (59)

*Numbers in parentheses refer to alternative modes of operation.

For many time-resolved experiments the average x-ray flux is not of consequence, but rather the number of photons per bunch is the important parameter. In Table II are listed the calculated photons per burst and instantaneous flux for both dipole and insertion device sources at the APS. All calculations are made at the critical energy (for dipole and wiggler sources) or at the fundamental energy (for undulator) assuming 7.0 Gev, 100 milliamp operation with 20 bunches. (Detailed information on the APS source properties can be found in reference[3].)

Table II

Source	No. of photons per burst	Instantaneous Flux
Dipole Source	1.7×10^{6} p/0.1%BW-mradθ	1.5×10^{16} p/s-0.1%BW-mradθ
Wiggler A	3.9×10^{7} p/0.1%BW-mradθ	3.4×10^{17} p/s-0.1%BW-mradθ
Wiggler B	4.5×10^{7} p/0.1%BW-mradθ	3.9×10^{17} p/s-0.1%BW-mradθ
Undulator A	2.1×10^{8} p/0.1%BW*	1.8×10^{18} p/s-0.1%BW*
Undulator B	1.7×10^{8} p/0.1%BW*	1.5×10^{18} p/s-0.1%BW*

*Integrated over the horizontal and vertical divergences of the central peak.

By adjusting the bandwidth of the monochromating system large increases (10 to 100) in the number of photons per burst can be obtained with dipole and wiggler sources and to a lesser extent with undulator sources, since these have a natural line width of 1%.

Several questions relating to the temporal properties of the APS have been put forth by researchers interested in performing time-resolved x-ray measurements. These questions have centered around concerns about bunch size and stability and the degree of "emptiness" of RF buckets adjacent to a filled bucket. From discussions with the accelerator design group, the following additional properties have been estimated: (1) The number of particles in each bunch (i.e., the current per bunch) should be the same to within ± 5% at the start of a fill. (2) A conservative estimate of the time jitter between the arrival of consecutive bunches should be less than 1 σ of the bunch length. This corresponds to ± 58 psec in 177 nsec (20 bunches equally distributed around the ring) or ± 0.03% of the interpulse period. (3)

Buckets adjacent to filled buckets would in fact be very empty, due in part to the fact that the injected bunch-length is 1 nsec while the RF bucket is 2.83 nsec in length.

As we pointed out earlier, the temporal parameters of the APS running in the (projected) normal mode will not be optimal for all experiments; in particular those experiments where "long" periods of darkness (>177 ns) are required preceding (succeeding) the burst of x-rays. From an operational viewpoint, the easiest solution to this problem is to run the storage ring in one-bunch mode resulting in an interpulse period of 3.536 microseconds. Assuming that the normal operational mode is twenty bunches, this would mean a corresponding decrease of the average flux by twenty, an unacceptable situation for the remainder of the users. (There may be the possibility of putting more than 5 milliamperes of current in each bunch, but this would be at the expense of beam stability; we will not consider this alternative here.) For those interested in monochromatic radiation, several proposals have been put forth to alter the time structure of the beam through the use of modulating monochromators(4). For the white beam, the possibility of using fast kicker magnets (wobblers) that can deflect one (several) positron bunch(es) out of the nominal orbit for a short distance has also been suggested as a means of altering the natural time-structure of the storage ring. In this scenario, one would arrange the experiment to see only photons from the deflected bunch(es). In principle, one could continuously vary the effective repetition rate of the x-rays in this fashion (up to the limit of the repetition rate of the kicker magnets.) Compared to one-bunch operation, this technique would be much less of a perturbation on the other users of the storage ring, <u>if</u> the kicker magnets had no effect on the overall beam stability, emittance, or lifetime. Concern over the possibility of perturbing the stability or other properties of the beam with wobblers has led us to consider other, more passive, options of modifying the natural time structure of the radiation.

One alternative approach to this problem involves the utilization of asymmetrically spaced bunches in the storage ring in concert with choppers. Recall that the standard running condition for the APS (at the time of this writing) is with 20 evenly spaced bunches (See Fig 1a). In our asymmetrically filled mode, 19 of the 20 circulating bunches would be injected into contiguous (or closely spaced) RF buckets and one bunch placed diametrically opposite to them (See Fig. 1b). This arrangement would allow the use of a slotted mechanical chopper, rotating at approximately 18,000 RPM, to pick out and transmit radiation from the lone pulse and block the subsequent pulses so that long interpulse periods could be achieved. With a single chopper having a rotational period equal to a multiple of the orbital period ($T_{chop}=nT_{orbit}$, n an integer) interpulse periods from approximately 3 microseconds to 3 milliseconds can be achieved by tailoring the slot configuration in the wheel. For longer interpulse periods, two choppers in series can be used. In the following section the characteristics of the type of choppers that would be needed are outlined.

Chopper Characteristics

Neutron or Fermi choppers have been extensively used over the past forty years both to monochromate and produce short pulses of neutrons[5]. Fast choppers consist of four main mechanical components: (i) an evacuable housing, (ii) the chopper or slit assembly, (iii) bearing assembly, and (iv) the drive motor. Typically the housing is evacuated to several Torr to reduce drag from the air. A crucial component, particularly for high speed choppers, is the bearings, some of which rely on sophisticated magnetic suspension systems. Although the types and ratings of the motors used vary widely depending on the particular applications, these motors usually have power ratings of several hundred watts. The slit assemblies are rather complicated components whose shape depends upon the specific job of the chopper. Since this part of the neutron chopper is least relevant to our needs, we will not dwell on this aspect of the chopper assembly. The electronics for control of the choppers is beyond the scope of this note. (See some of the chopper references for more information on the control systems.)

Our application of chopper wheels to synchrotron radiation is not to define the length of the burst, but rather to control the repetition rate by allowing one (or several) bunch(es) of x-rays to pass through and onto the experiment while blocking unwanted bursts. When the storage ring is running with 20 evenly spaced bunches this requirement translates into the need to block or close an aperature in less than 177 nsec. (In the following discussion we will assume that the vertical extent of the beam is limited to 1/2 mm. This is approximately the vertical height of the central peak of an undulator beam at a distance of 20 meters from the source, while for wiggler or bending magnet sources this size might be achieved by vertical focusing optics and/or slits.) The shutter speed required to block a 1/2 mm aperture in this time is in excess of 2800 meters/second, a difficult value to achieve. In the asymmetrically filled mode, the time between the lone bunch and the packet of bunches is approximately half the orbital period or 1742 nanoseconds, and hence the speed now required is ~ 1/10 that of the previous value, or 287 m/s. If the slot in the chopper wheel is the same size as the beam height (a constraint which minimizes the peripheral speed requirement of the chopper), then for a wheel 30 centimeters in diameter a rotational frequency of about 18,000 RPM would be sufficient (see Fig. 2). If this chopper is phased to the storage ring and has a rotational period equal to some multiple of the ring orbital frequency, a singly slotted wheel would transmit one x-ray burst every 3.33 milliseconds while a fully slotted beam (0.5 mm slots spaced 1 mm apart) would transmit pulses every 3.5 microseconds.

Although 18,000 RPM may at first consideration seem high, neutron choppers operate routinely at these and higher rotational frequencies. It is of interest to point out, however, that by using a pair of counter-rotating phased chopper wheels, only half the rotation frequency or approximately 9000 RPM is required (see Fig. 3). Although more complex than a single rotating chopper, this configuration has the additional advantage that by rotating the second chopper at a slightly different frequency, the alignment of the slots in the two wheels occurs at times given by the beat frequency between the two wheels. With a $\Delta\nu$ of 20 RPM, the minimum allowable so that there is no slot overlap for successive bursts of x-rays transmitted by the up-stream chopper, a 6 second interpulse period can be realized. Alternatively rather than using a single chopper wheel with a rotation axis parallel to the beam direction, a squirrel cage arrangement could be employed (see Fig. 4). In this case the axis of rotation is perpendicular to the x-ray beam direction and only half the single wheel rotational frequency is necessary to block the 1/2 mm aperture. (This configuration might require a slotted rotation shaft, but this should have no major impact on the performance of the wheel.) An effort investigating the mechanics and electronics of such chopper wheel arrangements is underway.

Conceptually, the x-ray chopper would consist of a circular plate (preferably a high strength lightweight material) onto which is mounted a slotted annulus of high z material (tungsten, tantalum, etc). To estimate the thickness of high z material required, we will assume that we want the x-ray flux transmitted through the annulus to be 0.1% that of what is passed through the slot. A wheel with one slot rotating at 18,000 RPM passes one burst every 3.3 millisecond, and hence must block in that same time approximately 20,000 equally intense pulses. Our requirement that the 'leakage' be 0.1% of the transmitted beam translates into a ratio $I/Io=2x10^{-7}$ or a μt of 15.4. Assuming that the undulators reach 20 keV in the fundamental, we will calculate the thickness using the absorption coefficient necessary to stop the highest energy third harmonic, i.e. 60-keV photons. For a tungsten annulus, a thickness of 1.5 mm would be required. For a one-centimeter-wide annulus 30 centimeters in diameter, the corresponding mass would be 0.27 kg. A typical backing plate might have a mass of approximately 1 kg. The combined moments of inertia of the backing plate and annulus would be in the range of 200-300 $kg\text{-}cm^2$. This very crude estimate did not include the shaft inertia; however, the point of this exercise is to give one a feeling of the magnitude of the problem. As was alluded to earlier, neutron choppers run in the range of 20,000 RPM (with some exceeding 30,000 RPM[6]) and have typical moments of inertia of 500 $kg\text{-}cm^2$[7] and so choppers such as those required here are certainly in the realm of current engineering technology.

A serious concern when dealing with these high speed choppers is their speed/phase stability. Neutron chopper wheels have been operated with phase stability of ± 0.2 μsec.(6) Two manifestations of chopper instability are (1) a decrease in the intensity of the transmitted burst and/or (2) the addition of satellite bursts near the burst of interest (see Fig. 5). The consequences of instabilities in x-ray choppers can be minimized, I believe, at the cost of increased peripheral wheel speed. Because the time required for the x-ray burst to pass through the slot is so small (116 psec) during the passage one can consider the slot in the wheel as frozen in time. (Even with a peripheral speed of 500 m/s the distance the slot moves during the time the x-ray bunch is passing through the slot is 600 Å.) Therefore, increasing the wheel speed has no effect on the transmission of the pulse but can aid in blocking satellite peaks that get through due to instabilities. Fig. 6 shows the case in which the 1/2 mm aperture is required to be closed in 1.5 μsec rather than 1.7 μsec. In this case we must increase the revolution frequency from 18,000 RPM to 21,200 RPM. At this speed the slot can still completely block the neighboring burst of x-rays with a chopper jitter of ± 0.2 μsec but at the expense of a reduction in the transmitted x-ray intensity by 13%. By going to higher speeds, even this problem can be reduced. If, instead of having a beam height and slot height of equal dimensions, we open the size of the slot, the transmission function of the wheel is no longer sawtooth in shape, but now has a truncated sawtooth form. We can easily calculate the required slot size necessary to have the plateau in the transmission function last for 0.4 μsec -- in this case, a slot of height 0.654 mm. This situation can be seen schematically in Fig. 7. In this case we can tolerate a ± 0.2 μsec jitter with no loss of transmitted intensity and no satellite peaks. As before the cost is an increase in revolution frequency from 21,200 RPM to 24,500 RPM. However, I reiterate that these rotational frequencies are achieved by state-of-the-art neutron choppers.

Summary

We have presented here what may be a viable approach to the problem of altering the natural time structure of the APS with a minimal impact on other users. Our technique involves placing 19 of the 20 circulating bunches of positrons in (nearly) contiguous RF buckets and the remaining one bunch 180 degrees around the ring from this pack. The method we are advocating has several advantages over other schemes (such as wobblers) in that it is a passive technique: there are no external forces on the particle beam to destroy its stability, emittance, or lifetime properties, and it will not limit the total number of bunches in the beam to one (or a few) in order to get long dark periods between x-ray bursts. In this configuration it should be possible to transmit the lone bunch and mechanically shutter the remaining 19 bunches with a chopper running at approximately 18,000 RPM. Although high, such revolution frequencies are achieved in neutron choppers which are generally much more massive than what is envisioned for an x-ray chopper.

There may be certain classes of one-shot experiments where the number of photons from one burst is not enough, but perhaps photons from 10 or 20 bursts would be adequate. For such experiments an interesting variation of our chopper scheme is to block the lone bursts of x-rays, allowing the pack of 19 bursts to pass. In the standard operating mode it would take 3.536 micro-seconds before all 20 bursts of x-rays have illuminated your sample. In our asymmetrically filled mode, one can get 95% of the corresponding number of photons (19 out of 20 bunches) not in 3.5 microseconds but in about 51 nanoseconds (assuming the bunches are in contiguous RF buckets) which translates to an increase in effective flux (or alternatively an increase in the temporal resolution) by a factor of almost 70!

Several concerns deserve mention when considering asymmetric bunch stacking. First and foremost is whether this mode will have detrimental effects on the storage ring performance. This is an area where I have no expertise and can only point this out as a possible problem. Although discussions with the accelerator physics group have indicated that the injector can fill the ring in this mode, will there be unforeseen problems in lifetime, beam stability, maximum current limit, etc.? If feedback systems are planned to be used, will this mode of operation require an increased bandwidth in the electronics? Certainly these potential problems (and others) must be explored. A second concern deals with single photon counting statistics in this running mode. A majority of the single photon counting detectors currently used at synchrotron radiation sources would not be fast enough to distinguish multiple x-rays that come from the 19 closely spaced bunches. Hence, in order to avoid pulse pile-up problems, the detector count-rate would have to be maintained below the rate where the probability of collecting two or more photons from the 19 contiguous bunches is low. We can estimate the count-rates where pulse pile-up will become important in the following way. Consider a detector count rate, n, equal to the reciprocal of the orbital frequency (i.e., $n = 1/T_{orbital} = 282{,}000$ cps). On average, the detector is receiving one x-ray every time twenty bunches pass by. At higher rates two (or more) photons will be collected a majority of the time after the passage of 20 bunches and hence the probability that those two (or more) photons originated from the 19 closely spaced bunches increases rapidly. Therefore count-rates of less than, say, 100,000 cps may have to be maintained to minimize the pulse pile-up effect. This limit does not seem too severe, considering that count-rates higher that this can probably be handled with integrating detectors (ion chambers, x-ray diodes) if energy discrimination is not an issue.

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Captions

Fig. 1 Schematic of the time structure of the APS. In (a) is shown the normal filling configuration for 20 bunch operation while in (b) is shown a proposed asymmetric filling mode of 19 bunches in adjacent RF buckets and one bunch diameterically opposite. Note that the drawings are not to scale.

Fig. 2 Schematic of a single chopper wheel operating at 18,000 RPM. When the wheel is phased to the orbital frequency of the storage ring, one burst of x-rays will be transmitted through the slot every 3.3 msec. A higher repetition rate of transmitted x-rays can be produced with addition of more slots. The shaded area represents an annulus of high z material to block the unwanted x-ray bursts.

Fig. 3 Schematic of two counter-rotating chopper wheels. With counter-rotating chopper wheels, only half the peripheral speed (and hence rotational velocity) is required to close the same size aperture. An additional benefit of two tandem chopper wheels is that by having slightly different rotational frequencies x-ray pulses will be transmitted through both wheels with a frequency equal to the beat frequency of the two wheels. In this way, long (5 sec) dark periods can be produced between x-ray bursts. The control system for a phased array such as this is unfortunately more complicated than a single wheel electronics.

Fig. 4 Schematic of an alternative approach to an x-ray chopper. An alternative to the previously displayed choppers is the "squirrel cage" arrangement shown here. As with the dual chopper configuration, this chopper need only rotate at half the rate of a single wheel to produce the same result. Note that in this arrangement a slot would also have to be machined into the shaft to allow the x-ray burst to pass.

Fig. 5 Timing diagram of chopper wheel rotating at 18,000 RPM. Plotted here is the incident beam intensity vs. time (a), the transmission function of the chopper vs. time (b), and the transmitted beam vs. time (c). If there is a jitter of phase instability of 0.2 μsec this will manifest itself in the transmitted beam intensity as a reduction in the primary pulse (by about 13%) and the addition of satellite peaks around the primary peak.

Fig. 6 Timing diagram of chopper wheel rotating at 21,200 RPM. By rotating the chopper at a higher rate (as compared to Fig. 5) the transmission function can be made narrower, eliminating satellite peaks due to jitter; however the reduction in primary beam intensity is still present.

Fig. 7 Timing diagram for a chopper wheel rotating at 24,500 RPM with a slit (0.654 mm) larger than the aperture (0.5 mm). In this configuration the transmission function is no longer sawtooth shaped but now has a truncated top which can accommodate a ± 0.2 μsec jitter in the chopper wheel with no satellite peaks and no loss in primary beam intensity. This revolution frequency is still well within current engineering capability.

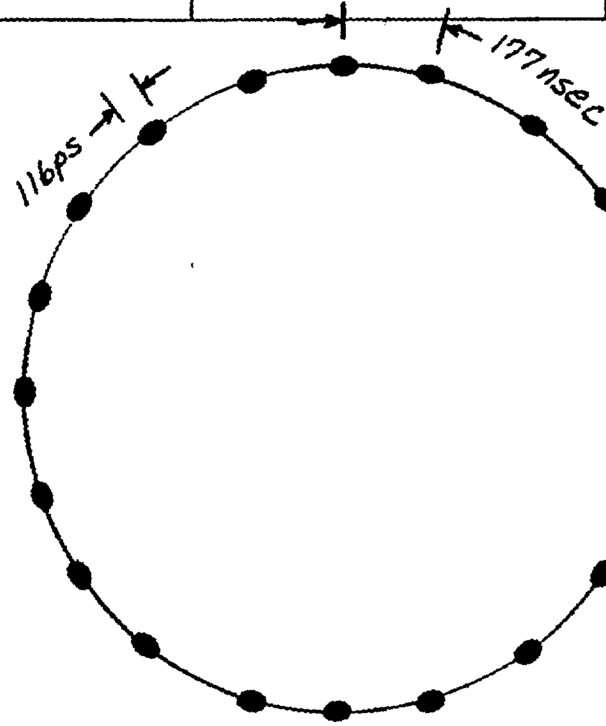


Fig 1a.

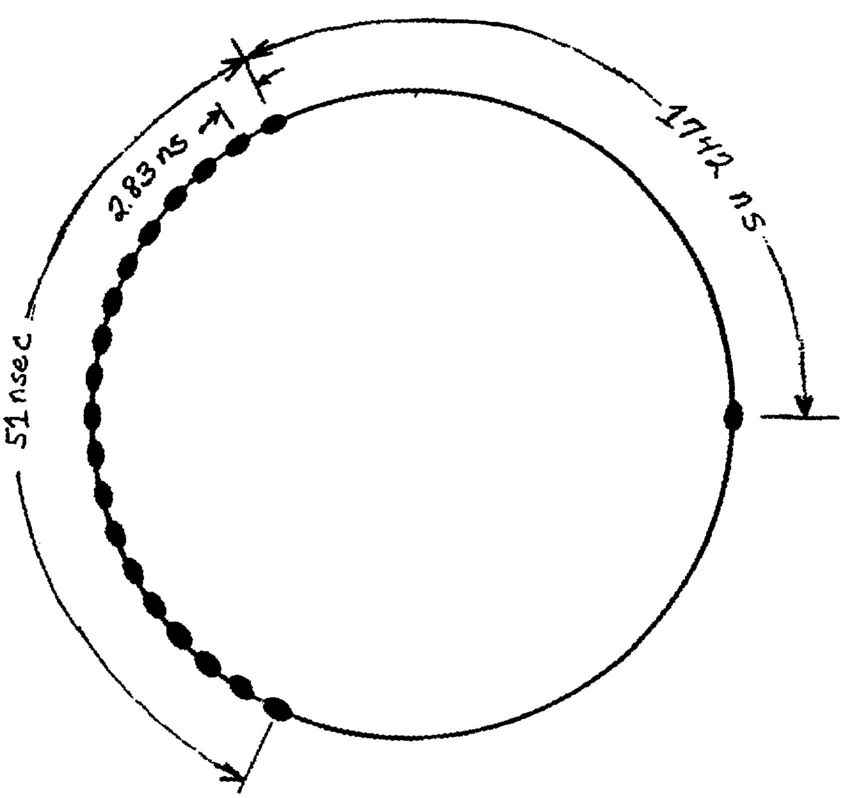


Fig 1b.

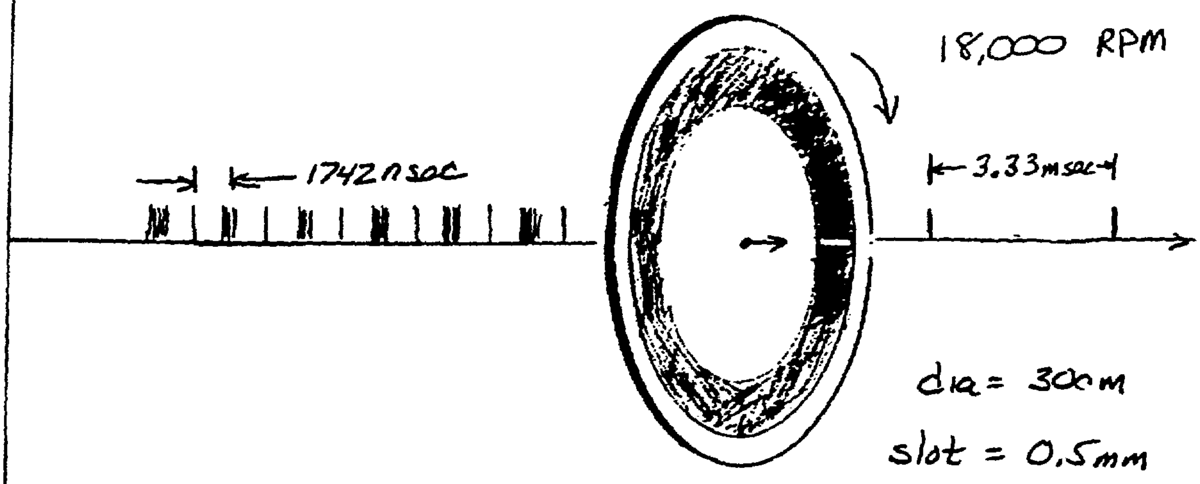
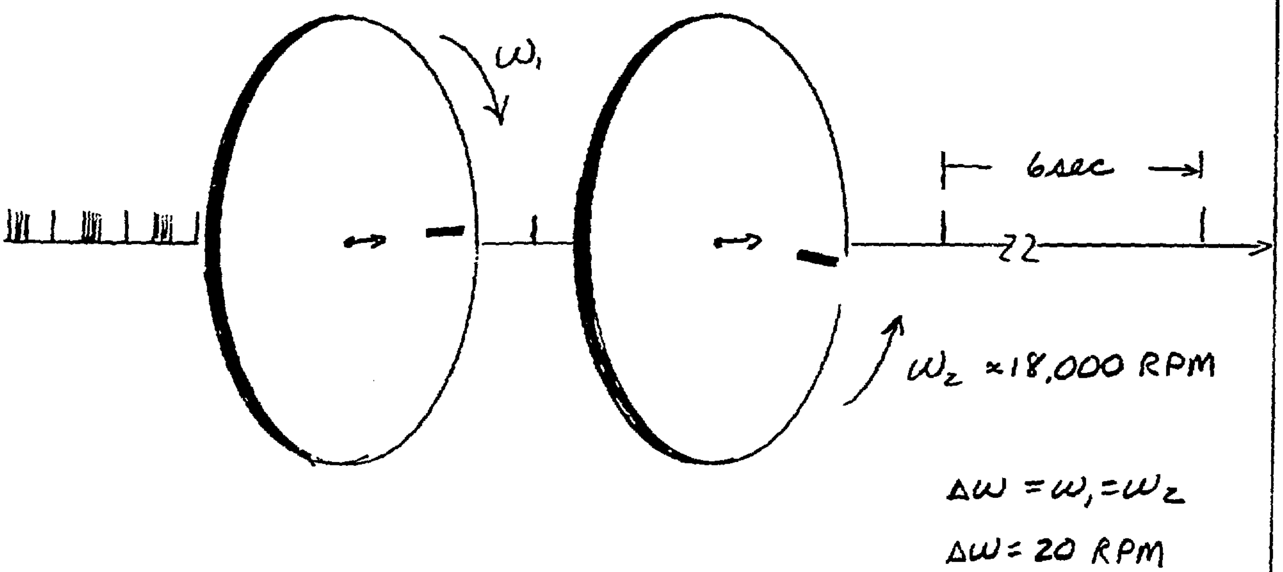

1742nsec
18,000 RPM
3.33msec
dia = 30cm
slot = 0.5mm

Fig. 2


ω_1
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$\omega_2 \approx 18,000$ RPM
$\Delta\omega = \omega_1 - \omega_2$
$\Delta\omega = 20$ RPM

Fig. 3

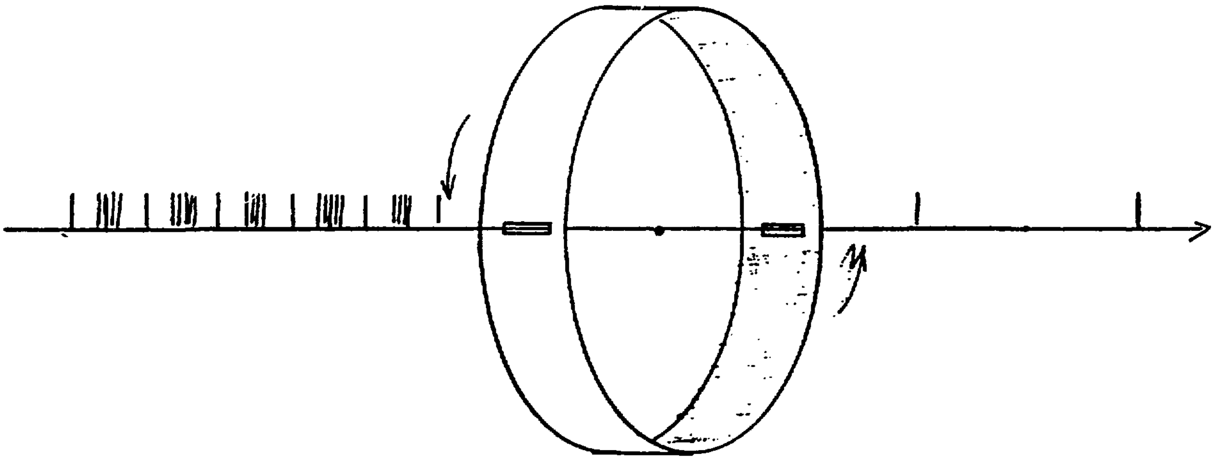


Fig. 4

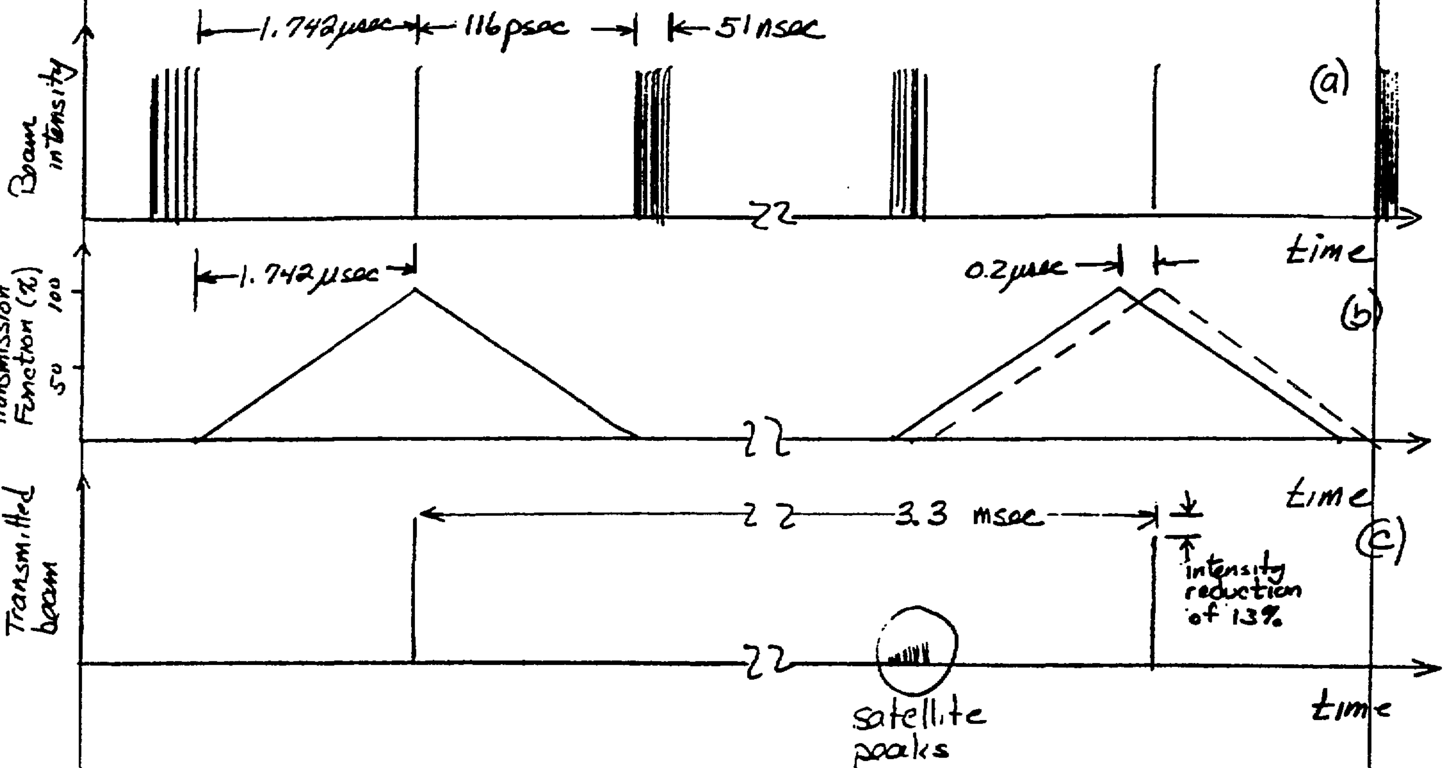
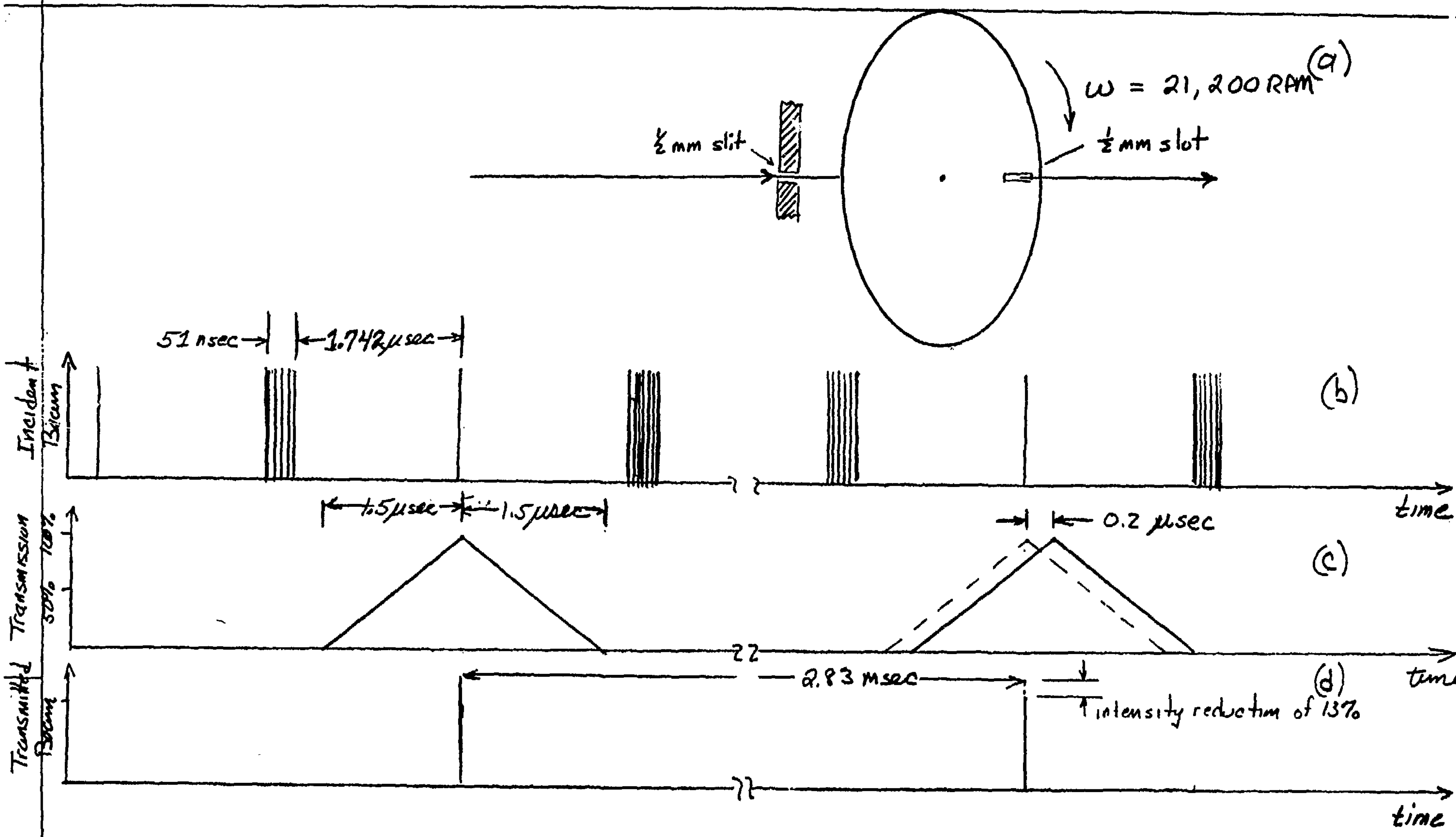

1.742μsec
116psec
51nsec
Beam intensity
(a)
time
Transmission Function (%)
100
50
1.742μsec
0.2μsec
(b)
time
Transmitted beam
3.3 msec
intensity reduction of 13%
(c)
satellite peaks
time

Fig. 5



ω = 21,200 RPM
(a)
½ mm slit
½ mm slot
51 nsec
1.742 μsec
Incident Beam
(b)
1.5 μsec
1.5 μsec
0.2 μsec
Transmission
50%
100%
(c)
time
2.83 msec
(d)
intensity reduction of 13%
Transmitted Beam
time

Fig. 6

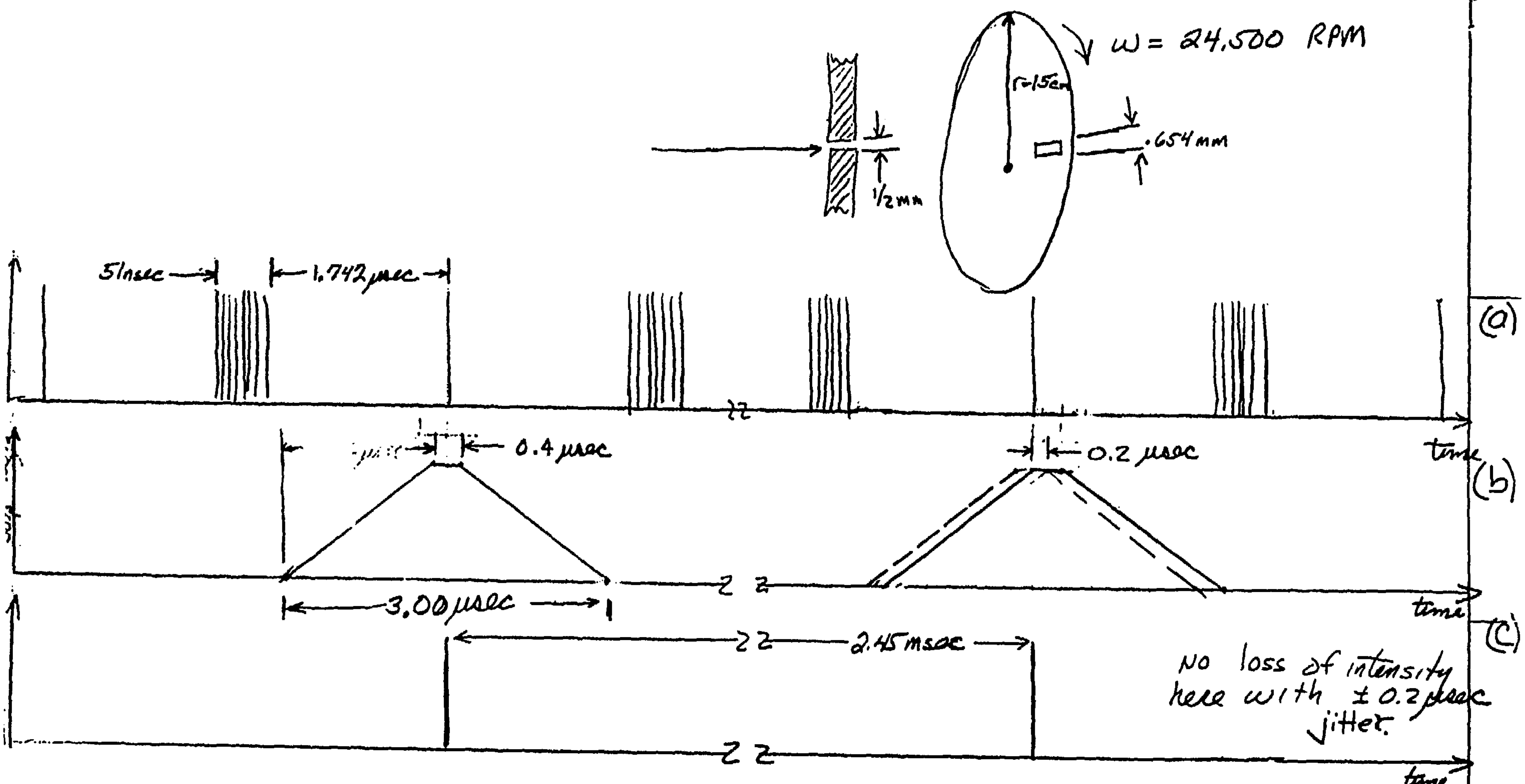

ω = 24,500 RPM
r=15cm
.654 mm
1/2 mm
51nsec
1.742 μsec
0.4 μsec
0.2 μsec
3.00 μsec
2.45 msec
(a)
(b)
(c)
time
time
time
No loss of intensity here with ± 0.2 μsec jitter.

Fig. 7