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AUTHOR(S): Roger W. Warren

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LASING ON HIGHER HARMONICS*

R. W. WARREN

Los Alamos National Laboratory, Los Alamos, NM 87545

Telephone (505) 667-1988, FAX (505) 667-0919

Abstract

Lasing at short wavelengths with an accelerator of modest energy can only be achieved with a wiggler of short period and high field operating, perhaps, at a high harmonic of the fundamental frequency. We discuss the characteristics of wigglers of this kind, designed to lase with harmonic numbers as large as fifty or so, emphasizing their gain, efficiency, and sensitivity to emittance and energy spread.

1. Introduction

There are two movements gaining popularity in the FEL community: shifting to shorter wavelengths and building smaller, less expensive FEL systems. The paths being followed to achieve these goals can be understood by examining the resonance equation,

$$\lambda = P(1 + K^2_{rms}) / (2\,\Gamma^2 H), \qquad \text{[Eq. 1]}$$

where P is the period of the wiggler, Γ is the relativistic energy of the electrons, H is the harmonic number, and K_{rms} is the wiggler parameter given by $K_{rms} = eP\,B_{rms} / (2\pi\,mc)$, where B_{rms} is the rms magnetic field on the axis of the wiggler.

Shorter wavelengths can be reached by increasing Γ, decreasing the period, or lasing on a harmonic. Increasing Γ is unattractive because it forces costs and size

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upwards, thwarting the second goal. Decreasing the period eventually leads to fabrication of microwigglers, an active field of current interest [1]. Lasing on harmonics is the topic of this paper.

Our purpose is to examine the advantages and disadvantages of producing a given wavelength by lasing on harmonics instead of the fundamental, to identify the critical issues, and to reach conclusions about the feasibility of such a plan. The rest of this paper is divided into section **2.** Gain on harmonics, section **3.** the Effects of emittance and energy spread, section **4.** Wiggler designs for different harmonics, and section **5.** Conclusions.

2. Gain on harmonics

It is difficult to analyze the possibilities of harmonic lasing because of the number of interacting variables. Our approach in this paper is to fix the wavelength and the important electron beam properties, current, energy, energy spread, and emittance, and to compare the maximum gain that can be achieved on the various harmonics with optimally-designed wigglers. We need a way to evaluate the gain of FEL systems that includes the effects of real e-beams and real wigglers. There are various ways to express the gain, depending upon which variables one wishes to emphasize. Dattoli et al [2] have given a particularly useful form that we have modified as follows:

$$\text{Gain} = .002\, I\, \Gamma\, F^2\, Q\, E_m\, E_n, \qquad \text{[Eq. 2]}$$

where I and Γ are the current (amps) and energy of the e-beam, F is the number of betatron cycles undergone down the wiggler by an electron ($F = N_w K_{rms} / \Gamma$, where N_w is the number of wiggler periods), Q is a factor less than one that depends on H and the K_{rms} value; E_m is a factor less than one that depends on the emittance of the e-beam, F, and λ; and E_n is a factor less than one that depends on the energy spread of the e-beam, H, and N_w.

In this formulation, Q, E_m, and E_n are gain reduction factors, while $.002\,I\,\Gamma\,F^2$ is the highest gain, G_{pk}, that can be achieved with a given beam power and wiggler. For a typical FEL, eg- the Los Alamos system with I = 300 amp, Γ = 40, N_w=40, K_{rms}=0.5, and F = 0.5, G_{pk} is 6. Figure 1 is a graph of Q vs K_{rms} for various harmonics. E_m and E_n have been approximated by Dattoli et al when they are not too small as

$$E_m = [1 + (2\,F\,\varepsilon/\lambda)^2]^{-1}, \qquad \text{[Eq. 3]}$$

where ε is the rms emittance of the e-beam and $\varepsilon_n = \varepsilon\Gamma$, where ε_n is the rms normalized emittance of the e-beam. For the Los Alamos FEL with a photocathode gun, $\varepsilon_n \simeq 30$ μm. Finally,

$$E_n = [1 + (5\,H\,N_w\,dE/E)^2]^{-1}, \qquad \text{[Eq. 4]}$$

where dE/E is the rms energy spread of the e-beam. For the Los Alamos FEL, dE/E $\simeq$0.3%

Now, we would like to maximize the gain. Clearly, there is a big advantage to making the beam power as large as possible. The current can be increased to hundreds of amps at little cost, but increases in Γ are to be avoided, being directly related to increases in size and cost. Gain will also increase with F, and thus wiggler length, until either E_n or E_m decreases rapidly, eventually, according to Eq. 2, saturating the improvements at some critical length.

A discussion of the optimization of wiggler length when emittance and energy spread are important is presented in section 3 below.

From fig. 1 it is clear that Q approaches 1 for the fundamental at low K_{rms} values but never exceeds 0.4 for all of the harmonics. Such low K_{rms} values are difficult to use with the fundamental, however, so K_{rms} values encountered in existing wigglers that lase on the fundamental are around 0.7. K_{rms} values from 1 to 4 are needed to maximize Q on the harmonics up to about the 61st. Reaching such high K_{rms} values, then, is an important consideration that will be discussed in section 4 below. If such

K_{rms} values can be generated, Q will be the same, within a factor of two, for the fundamental and all of these harmonics.

3. The effects of emittance and energy spread

A. Emittance

Clearly every effort should be made to reduce the emittance without compromising beam current. Efforts to accomplish this by using guns with photocathodes are very promising. Emittance reductions of 5-10 times, to $\varepsilon_n = 25$ μm, have been accomplished recently [3] and further reduction seems likely.

A reasonable choice for wiggler length gives $F = P/2\varepsilon$, ie- a value that makes $E_m = 0.5$. Shorter wigglers have less gain, but the gain saturates for longer ones. With this choice, the gain varies as $(\lambda/\varepsilon)^2$; so that short wavelengths can only be reached by sacrificing gain. A gain of ten percent (for Los Alamos parameters) can be achieved at a wavelength of 0.25 μm. Such wigglers will have very small periods (~1 mm) and will be unusually short, ie- $F \sim 0.2$, $N_w \sim 7$, and $L_w \sim 1$ cm. Note that the harmonic number does not appear explicitly in the formula for E_m, thus the considerations of this paragraph are valid for any harmonic.

B. Energy spread

Schemes have been devised to reduce some kinds of energy spread, but spread caused by wakefield effects in the accelerator is proportional to beam current and is hard to eliminate. A value of 0.1% appears to be hard to beat with high current beams.

If energy spread is the significant gain reducing factor, a reasonable choice of parameters in Eq. 4 is, as above, to make $E_n \sim 0.5$. Then $N_w = 1/(5\ H\ dE/E)$, and the gain varies as $(K_{rms}/H)^2$. If K_{rms} has been chosen to optimize Q for the harmonic H, this ratio, K_{rms}/H, depends very weakly on H, dropping from about 0.3 to 0.2 as H increases from 3 to 11. Thus the gain reduction factor caused by energy spread is only weakly dependent on harmonic number. Wigglers that satisfy this condition on N_w are not as short as those considered above, eg- if $dE/E = 0.3\%$ and $H = 3$, then $N_w = 25$. Thus, for $H = 3$ and the Los Alamos parameters, the emittance constraint on wiggler length is stronger than the energy spread constraint. The harmonic number can be increased, however, decreasing N_w, until the emittance and energy constraints both give the same value for N_w. This occurs when

$H = 0.4\,(\varepsilon/\lambda)\,(K_{rms}/\Gamma)\,(E/dE)$.

Using the Los Alamos accelerator parameters with $\varepsilon/\lambda = 3$ and $K_{rms} = 2$, we find $H \sim 21$.

Our conclusions from this kind of analysis is that:

1. With an appropriate wiggler design, a wavelength as short as 1/3 the emittance, ie- 0.25 μm for the Los Alamos parameters, can be achieved.
2. The period will be very small and the wiggler very short.
3. Any harmonic up to about the 21st can be used, producing about the same gain.

4. Wiggler designs for different harmonics

Solving the resonance equation for the Los Alamos accelerator and $\lambda = 0.25$ μm, we find $P = 0.8\ H/(1+K^2_{rms})$ mm. Figure 2 shows the period for different harmonics when K_{rms} is chosen either to give the peak value of Q, a lower K_{rms} that gives a Q value one-half of its peak (with a loss of a factor of two in gain), or an even lower K_{rms} that gives a Q value of 1/4 its peak. The shortest period, 0.5 mm, occurs for the fundamental; the longest, ~4 mm, is found at the highest harmonic.

Figure 3, a replot of fig. 2, shows the K_{rms} value that is required vs period for lasing on the different harmonics, for the same three choices of K_{rms}. Also plotted on fig. 3 is an estimate of the limiting K_{rms} value that can be achieved with permanent magnet wigglers. Only points below this curve are attainable. The only assumption involved in drawing this curve is that the peak wiggler field is limited to 1 Tesla by the properties of its magnets. Also shown on Fig. 3 is a curve representing the best that can be done with pulsed electromagnetic wigglers [4]. Only points to the right of this curve are attainable. The shape of this curve differs from the permanent magnet curve because the K-limit for electromagnets is set in a different way, ie- by excessive heating, that leads to a limit on K that equals some constant times the period squared. The value of this constant depends upon the details of the wiggler's design and the length of its pulse. The design shown is for a double-helix wiggler [4] driven by a 100 μsec pulse of current that raises its temperature by ~300 C. We have recently built and operated such a pulsed wiggler that falls on the point labeled O. Its field was limited by the available power supply and not its temperature. Clearly, permanent magnet wigglers are completely unable to satisfy our needs for any harmonic. Pulsed wigglers, on the other hand, can generate much larger fields, especially for the longer periods appropriate to the high harmonics. Whether or not pulsed wigglers can be built to approximate the curve of fig. 3 is the topic of recent investigations.

Not discussed, up to this point, is the necessity of encouraging the harmonic of choice while suppressing lasing on all of the undesired harmonics. Various techniques can be used, but a generally useful way to accomplish this using a unique wiggler design is described in another paper in these Proceedings [5].

Having shown that many harmonics have adequate gain with K values that are within reach, our final criterion for choosing the "best" harmonic to use involves the ease of building the various microwigglers. Any of these wigglers will be only a few centimeters long with a bore of 1 mm or so. Tolerances in its fabrication will be hard to hold. We, therefore, choose the largest size and, therefore, the highest harmonic (the 21st) acceptable on other grounds.

5. Conclusions

Our goal was to achieve as short a wavelength as possible with an electron beam of given energy. To accomplish this we must abandon the security of designing and building within safe boundaries, and instead push all of the variables to their limits. This includes making the following choices:

1. Make the beam current as large as possible and the emittance and energy spread as low as possible.
2. Choose a short wiggler so that the penalty incurred from the emittance and energy spread are minimized.
3. Use a pulsed electromagnetic wiggler so that the required high K_{rms} values can be attained.
4. Operate on a high harmonic so that the wiggler's length and its period will be large enough to be built with good accuracy.
5. Suppress the unwanted harmonics in some way.

Following these procedures, we believe that wavelengths in the ultraviolet can be generated by FEL systems of moderate size employing accelerators with an energy of 20 MeV or so.

6. References

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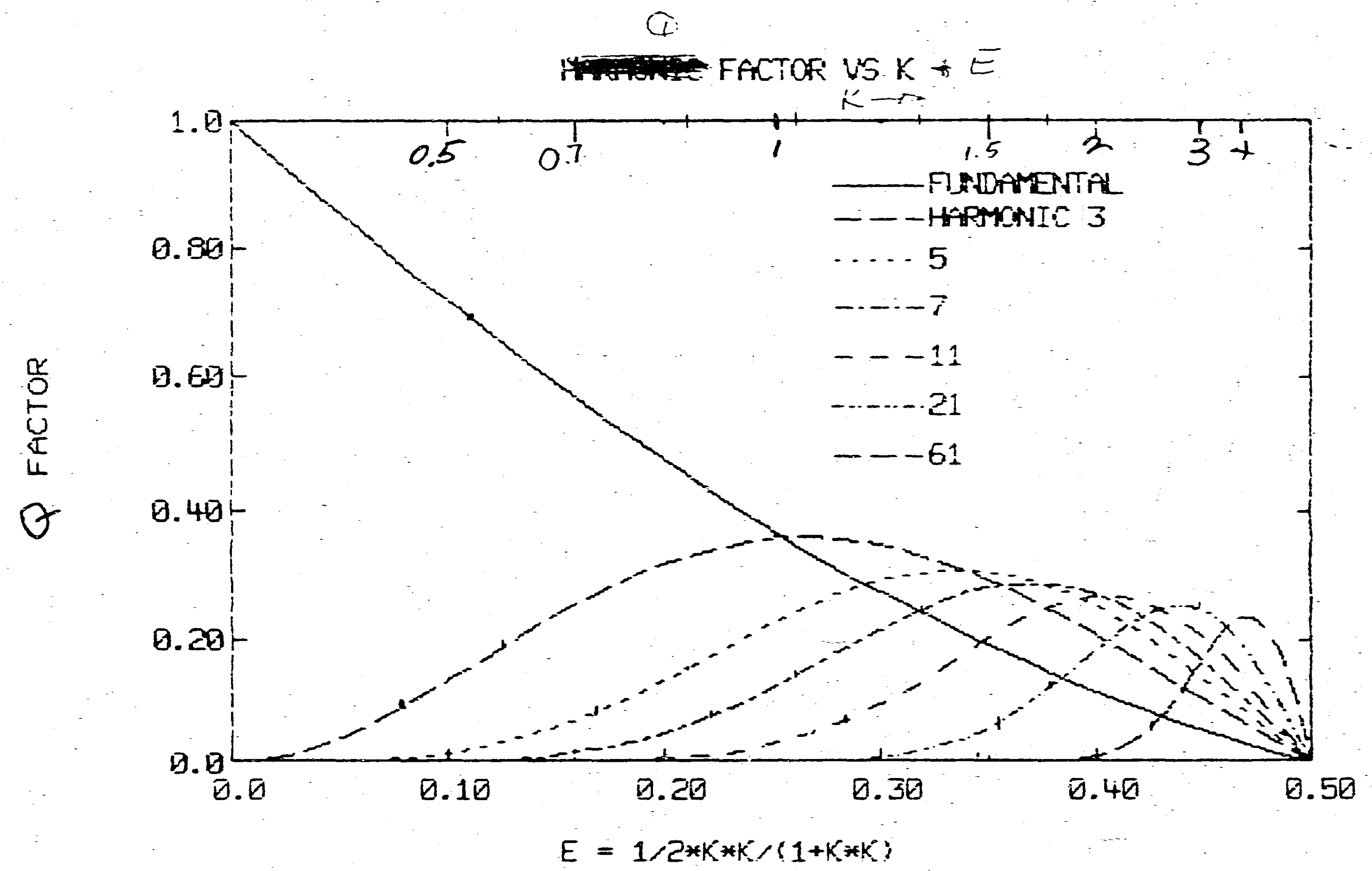
McKenna, "Performance of the Los Alamos HIBAF Accelerator at 17 MeV," these Proceedings.

[4] R. W. Warren, "Design Considerations for Pulsed Microwigglers," these Proceedings.

[5] R. W. Warren and N. Piovella, "Compound Wigglers Designed to Lase on a Selected Harmonic," these Proceedings.

7. Figure captions

1. The Q factor as a function of K_{rms} and E for the different harmonics.
2. Wiggler period vs harmonic number for three choices of K_{rms}.
3. K_{rms} value required for various periods and the values that can be achieved by permanent magnet and pulsed wiggler technologies. The periods that correspond to 0.25 μm light and various harmonics are shown.



Q
~~HARMONIC~~ FACTOR VS K + E
K
1.0
0.80
0.60
0.40
0.20
0.0
0.0
0.10
0.20
0.30
0.40
0.50
0.5
0.7
1
1.5
2
3
4
FUNDAMENTAL
HARMONIC 3
5
7
11
21
61
Q FACTOR
E = 1/2*K*K/(1+K*K)

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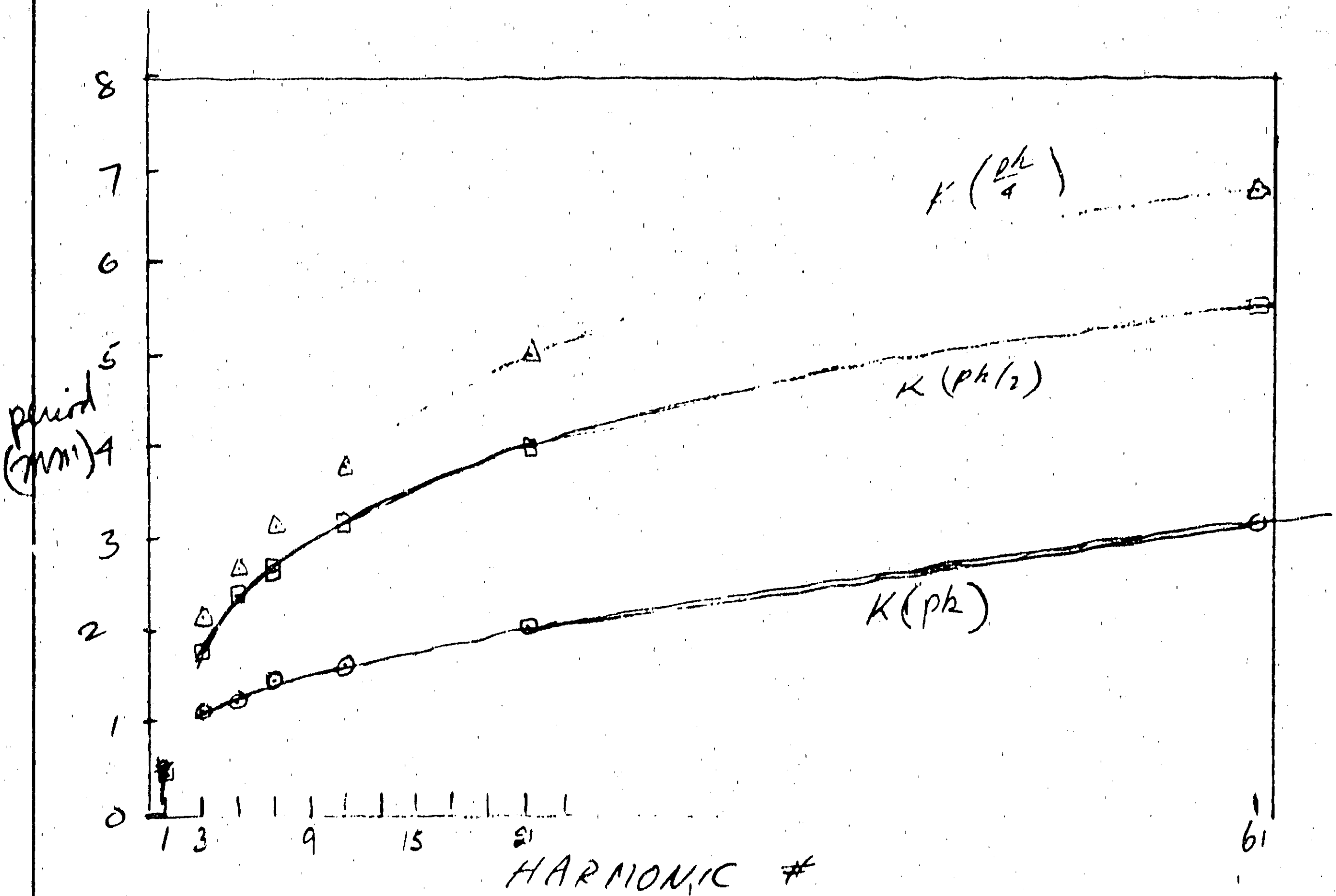

fig 2

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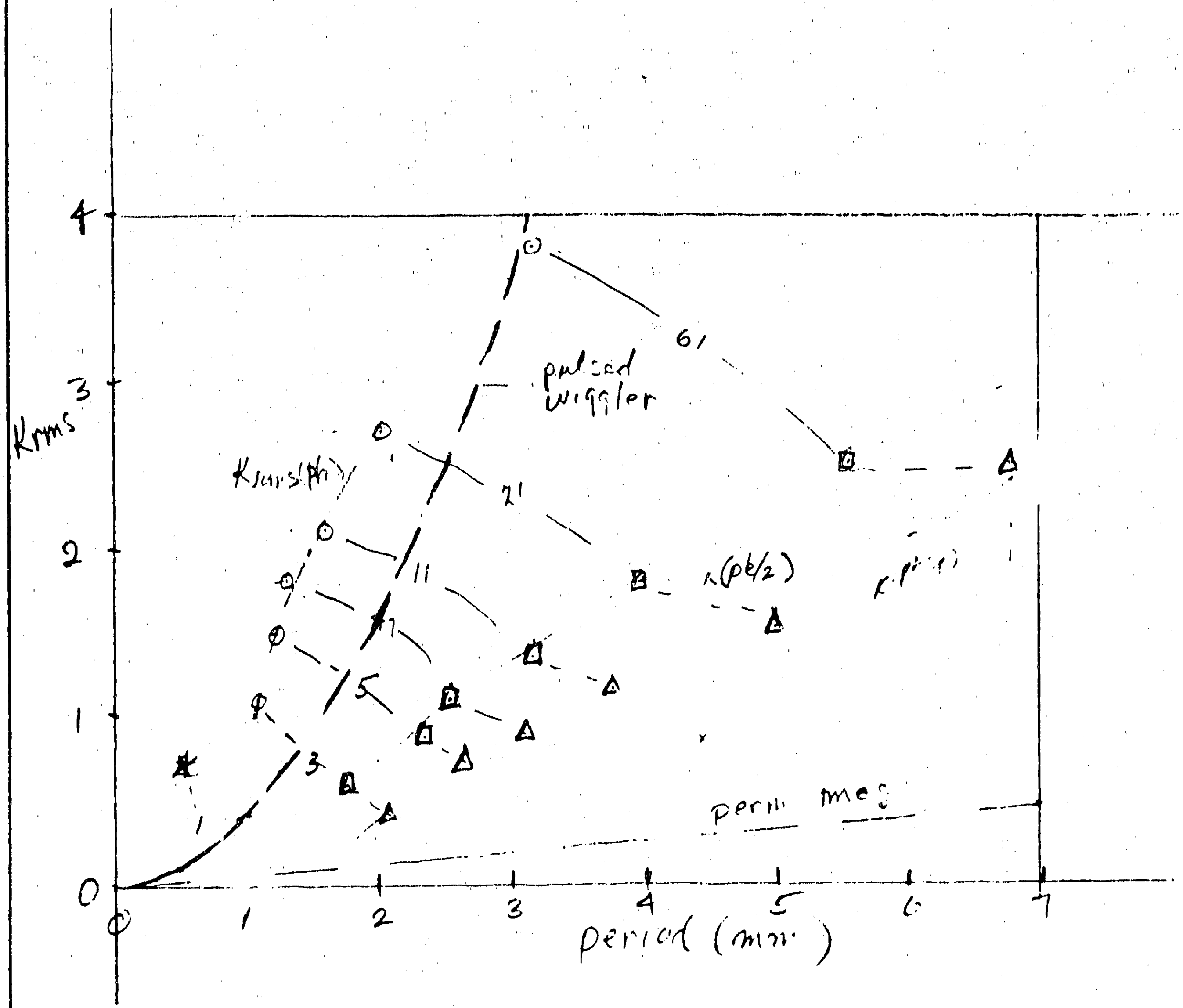

fig 3

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