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A ROTATING CRYSTAL PULSE SHAPER FOR USE ON A PULSED NEUTRON SOURCE

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ABSTRACT

A pulse shortening device is described for use on pulsed thermal neutron sources. The device employs rotating single crystals and has applications in the design of high resolution cold neutron spectrometers.

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1. Introduction

It is much more favourable to use white beam time of flight techniques on pulsed neutron sources than on continuous reactor-based neutron sources for reasons of neutron economy. However, from the moment of formation of the neutron burst in the moderator the white beam is correlated in wavelength and time unlike a beam on a continuous source and therefore neutrons of different wavelengths disperse as they travel from the moderator. This correlation provides the basis of the design of many pulsed source neutron spectrometers. In certain cases however it can be the cause of design constraints.

This is the case for the time of flight high resolution quasielastic spectrometer IRIS [1] to be built on the spallation neutron source SNS [2] at the Rutherford Appleton Laboratory. For this spectrometer a pulse of cold neutrons narrow in time but as wide as possible in wavelength is required. It is necessary therefore to reduce the moderator pulse width by chopping the beam as close to the moderator as possible in order to maintain an adequately wide incident neutron wavelength window. The distance of closest approach, and thus the wavelength window, is limited however by the intense radiation field in which the chopper must operate. A rotating crystal monochromator can produce a wider wavelength window than a mechanical chopper at the same position by matching the time of arrival of neutrons of different wavelengths in the incident beam to the time dependent Bragg condition of the rotating crystal. This paper explores the feasibility of such a device.

2. The λ-t representation of the neutron pulse

In λ-t space, where t is the time of arrival of a particular neutron of wavelength λ at a given distance L from the moderator, the neutron pulse can be represented by a straight line passing through the origin as shown in figure 1. Wavelength and time of arrival are related through the de Broglie relationship

$$\lambda = \frac{h}{mL} \cdot t \;\mp\; ct$$

Thus at a position close to the moderator this locus has a higher gradient, and far from the moderator a lower gradient reflecting the dispersion of the pulse with distance. For a given monochromatic neutron wavelength the time distribution of such neutrons is shown schematically in figure 2. A measure of the time width of the neutron pulse is given by the FWHM δt_M of this curve although this conceals the asymmetric shape of the pulse particularly the tail at long times. Nevertheless on the λ-t diagram the pulse width can be represented by separate traces for the leading and trailing edges of the pulse at the FWHM positions as indicated in figure 1. Note that the time distribution is independent of distance from the moderator and that δt_M is determined for the neutron pulse at the moment of its emission from the moderator surface and remains constant for each wavelength at all distances from the moderator. Consequently the principle parameter with which to vary the resolution of a spectrometer is its distance from the moderator and, for high resolution instruments, the required distance can become untenable. In these circumstances δt_M can be reduced in order to achieve the desired resolution. δt_M is proportional to wavelength in the slowing down region of the spectrum ($\delta t_M \sim 7\lambda$ where λ is expressed in Angstroms and δt_M in microseconds). In the thermalised Maxwell-Boltzmann region of the spectrum the pulse broadens and the constant of proportionality rises to between 12 and 25 [2,4].

The pulse narrowing necessary to attain high resolution can be achieved by two methods:

- The moderator itself can be designed such as to provide the pulse structure required by a particular spectrometer. However, since a number of spectrometers, in general, view the same moderator there is a limited, but nevertheless important, scope for this option.

- The pulse itself can be tailored after formation by some mechanism. This can be achieved by the use of a mechanical chopper but, as its alternative name of velocity selector implies, this greatly reduces the wavelength distribution in the beam transmitted by the chopper. This can be seen in figure 3 where we restrict our attention to a relatively narrow range of wavelengths. In this case the neutron pulse at a fixed distance from the moderator can be represented by two approximately parallel lines in λ-t space.The action of the chopper, of burst time δt_C, restricts the wavelength component in the transmitted beam to a relatively narrow range $\Delta\lambda$, particularly when $\delta t_C < \delta t_M$. Thus one advantage of the pulsed source - its white beam - can be severely limited in the design of high resolution instruments.

An idealised pulsed shortening device would reduce the pulse in time whilst maintaining its full wavelength range. This ideal case is indicated by the dashed lines in figure 3. A rotating crystal assembly, as described in the following section, more nearly approaches this ideal than does a chopper.

3. The rotating crystal pulse shaper

3.1 The basic principle

Suppose we arrange a single crystal, rotating with a constant angular frequency ω, at a distance L from the moderator as shown in figure 4. Then as initially fast and later slow neutrons illuminate the crystal, the rotational motion adjusts the Bragg angle Θ_B to reflect a continuous broad band of wavelengths whilst only remaining in the reflecting position for any particular wavelength for a time short compared to the intrinsic neutron pulse width δt_M from the moderator.

3.2 Phasing

Correct phasing of the crystal with respect to the time origin of the neutron pulse will enable the resulting sinusoidal locus of the beam reflected from the rotating crystal in λ-t space to form a tangent to the moderator neutron pulse locus as shown in figure 5. The crystal locus is given from Bragg's law as

$$\lambda(t) = 2d \sin \Theta_B(t) \tag{1}$$

where

$$\Theta_B(t) = \omega \, (t - t_o^*)$$

and t^*_o is a time origin for the crystal (equivalent to the time when the crystal planes are parallel to the incident beam).

Its gradient is given by

$$\frac{d\lambda(t)}{dt} = 2d \cos \Theta_B(t) \cdot \frac{d\Theta_B(t)}{dt}$$

By setting this gradient at a particular wavelength equal to the gradient c of the pulse from the moderator we obtain an expression for the crystal frequency ω required to reflect a neutron wavelength λ^* at time $t^*(= \lambda^*/c)$.

Hence

$$\omega = \frac{d\Theta_B(t)}{dt} = \frac{h}{mL\ [(2d)^2 - \lambda^{*2}]^{\frac{1}{2}}} \qquad (2)$$

3.3 <u>The wavelength and time windows</u>

Figure 6 illustrates the general case of the interaction of the rotating crystal pulse shaper with the moderator pulse in which the traces in λ-t space intersect. The half-height contours of the pulse are represented by the lines

$$\lambda = c(t \pm \delta t_M/2) \quad \text{where } c = \frac{h}{mL}$$

The rotating crystal, phased to be in reflecting orientation at time $t^* = \lambda^*/c$, reflects neutrons of wavelength λ at time t given to first order by

$$\lambda \simeq \lambda^* + c' \, (t - t^*)$$

$$= c' \, (t - t_o^*)$$

where c' is the gradient of the sine wave trace from the crystal and is given by

$$c' \equiv \omega \, [(2d)^2 - \lambda^{*2}]^{\frac{1}{2}}$$

$$= 2\omega d \cos \Theta_B(t^*)$$

$\Delta\lambda_c$ is the wavelength band reflected at a particular Bragg angle and is given by $\Delta\lambda_c = 2d \cos \Theta_B \Delta\Theta$, where $\Delta\Theta$ is the range of Bragg angles contributing to the reflection process and is a measure of the divergence of the reflected beam.

$\Delta\lambda_M$ (= $c \Delta t_M$) is the wavelength band transmitted by the chopper whereas the overall wavelength band of neutrons selected by a rotating crystal can be seen from figure 6 to be

$$\Delta\lambda'_M = \Delta\lambda_M \frac{c'}{c' - c}$$

$c'/(c' - c)$ is the wavelength band gain factor of the crystal over the chopper and for $c' = c$ the selected band becomes very large but not arbitrarily so inasmuch as the arguments here are based on a linearized treatment. A numerical solution of the problem is presented in section 4 where a realistic value of the wavelength band reflected can be estimated for the case when the two curves are tangential.

3.4 The burst time of the rotating crystal

The burst time of the rotating crystal determines the resolution of the system and is equivalent to the chopper burst time in determining the overall resolution of a chopper spectrometer. The time width of the reflected neutron pulse for a particular wavelength, caused by the inherent divergences of the beam, is given by

$$\Delta t_c = \frac{\Delta \lambda_c}{c'}$$

This is dependent on the incident and exit collimations α_1 and α_2 and on the mosaic spread β of the crystal and is equal to $\Delta\Theta/\omega$. This factor can be identified with the scan time contribution to the resolution of a reactor based rotating crystal spectrometer which is given in [5] as:

$$\Delta t_c = \frac{\Delta\Theta}{\omega} = \frac{1}{\omega}\left[\frac{\alpha_1^2\,\beta^2 + \alpha_1^2\,\alpha_2^2 + \alpha_2^2\,\beta^2}{\alpha_1^2 + \alpha_2^2 + 4\beta^2}\right]^{\frac{1}{2}} \qquad (3)$$

The approach is only valid provided that the scan time is shorter than the moderator burst width, ie the pulsed source appears to be a continuous source for the duration of the reflection of a particular wavelength. In this case where cold neutrons are employed and collimations are $\sim 1^{\circ}$ then crystal rotational frequencies above 25 Hz ensure its validity.

The pulse formed by the rotating crystal pulse shaper does not appear to diverge from either the crystal or the moderator. Rather the pulse appears to have been formed at a distance $L = \frac{h}{m}\left(\frac{1}{c} - \frac{1}{c'}\right)$ downstream from the moderator, and at a time $t_o^* = \lambda * \left(\frac{1}{c} - \frac{1}{c'}\right)$ after the moderator pulse itself.

3.5 The Doppler Effect

Since the monochromator crystal is moving with respect to the incident neutron beam the presence of the Doppler effect on the reflection process must be assessed.

The Doppler effect serves, for a particular point in the rotating crystal, to vary (i) the Bragg angles of incidence and reflection in the laboratory frame (ii) the selected and reflected wavelengths and (iii) the point in time of the reflection, each with respect to the equivalent parameters for the case of a stationary monochromator [6]. Considering the whole volume of the crystal this causes a broadening of the wavelength band selected, the time of reflection and the divergence of the reflected neutron beam. However, in the plane denoted AA in figure 7 (a) which is perpendicular to the Bragg reflection planes and passes through the axis of rotation, the Doppler effect does not manifest itself. In this plane the direction of motion is perpendicular to the momentum transfer vector in the reflection process and therefore the Doppler effect becomes negligible. This can be achieved in practice by using plate crystals in Laue transmission geometry (figure 7 (b)).

The Doppler effect has been used to advantage in focussing rotating crystal spectrometers on continuous neutron sources [5,7] but it appears impossible to fulfill all these conditions on a pulsed source where the incident beam is already correlated in energy and time. In particular the focussing conditions employed in rotating crystal spectrometers require that the crystal be rotated in the opposite sense to that required for this application.

3.6 Practical Considerations

Because of geometrical and shielding constraints the tailored neutron beam should emerge from the neutron source radially.

This can be achieved with the set-up shown in figure 8 (a) where a second identical crystal is phased with the first to reflect the neutron beam into the primary drift path of the spectrometer. In practice there also requires to be a translation of one crystal with respect to the other in order to satisfy the Bragg conditions for all wavelengths.

A second method is for the two crystals to be mounted on a single rotating table either with the first crystal located centrally and the second eccentrically (figure 8 (b)) or with both crystals positioned symmetrically with respect to the axis of rotation of the rotating table (figure 8 (c)).

In all cases the motion of the two crystals approximates well the rotational and translational motions required to satisfy the conditions described previously without significant degradation by the Doppler effect.

4. A Numerical Solution

In order to assertain the possible gain of a rotating crystal over a chopper we will compare the performance of the two systems constrained to the design specifications of the IRIS quasielastic spectrometer to be installed on the SNS [1].

4.1 The IRIS spectrometer

IRIS is a high resolution (1 μeV) quasielastic spectrometer. It operates by defining a neutron pulse at 4.4 metres from the moderator, allowing this pulse to disperse 40 metres to the sample position, and analysing the scattered beam by backscattering from an array of silicon analyser crystals. In the design of the IRIS spectrometer the beam definition is by a 12 μsec burst time chopper and the analysing wavelength of the silicon (111) reflections in backscattering is 6.28Å.

The wavelength window transmitted by the chopper, taking the half height positions as limits and a pulse width of 25 λ , is 0.14Å, corresponding to an equivalent energy band of 93 μeV. For comparison the backscattering spectrometer IN10 at the ILL, Grenoble has an energy band of $\pm$ 15 μeV ($\pm$ 0.023Å) and a resolution of $\sim$ 1 μeV.

The rotating crystal device with which to replace the chopper must use monochromators with a Bragg cut off greater than 6.28Å. The obvious choice is graphite with a Bragg cut-off of 6.69Å and a reflectivity for cold neutrons approaching 100%.

4.2 The application of graphite crystals

The maximum useful wavelength window $\Delta\lambda$ is reflected when the crystal locus and the pulse are tangential at 6.28Å. From equation 2 there is a reciprocal relation between crystal frequency and the distance of the crystal from the moderator. In order that periodic phasing occurs the crystal frequency must bear an integral relationship to the pulsed source frequency. For the SNS this frequency is 50Hz. Therefore one can define a series of distances each corresponding to a particular crystal frequency. The times of arrival t* of 6.28Å neutrons (λ *) at these distances can thus be determined and, from equation 1, the values of t_o*, the time origin of the crystal rotation. Therefore one has a limited choice of distances at which to locate the crystal if one choses to reflect the maximum wavelength band. These distances are given in Table 1.

Crystal Frequency (Hz)	Moderator-crystal distance (metres)
25	10.92
50	5.46
75	3.64
100	2.73

Table 1 The relationship between crystal position and frequency

The intersection of a sine wave and a straight line has, surprisingly, no analytical solution and so the equations have been solved numerically using the data in Table 1.

A graphical solution for 50 Hz is shown in figure 9. The required scan time of the crystal is a factor of ten less than the moderator pulse width and therefore for convenience in the calculations of wavelength windows this width is assumed to be negligible. On an expanded scale in figure 10 it can be seen that one can increase the wavelength window substantially by phasing the crystal to the leading edge of the pulse [figure 10 (b)] rather than its peak [figure 10 (a)]. The resulting wavelength windows are given in Table 2 together with the wavelength window which would be obtained from a chopper in the same position.

Crystal Frequency (Hz)	Wavelength Window (Å)		
	Crystal		Chopper
	Peak Centre	Leading Edge	
25	0.44	0.62	0.06
50	0.63	0.86	0.115
75	0.75	1.05	0.17
100	0.87	1.21	0.24

Table 2 The wavelength windows transmitted by a chopper and a rotating crystal assembly for the conditions given in table 1.

These values, converted to units of energy are shown in table 3 and plotted in figure 11 as a function of frequency and distance. For operation of the crystal at 50 Hz at a distance of 5.46 metres the energy window is estimated to be 567 μ eV when phased to the leading edge of the pulse. This can be compared with the value of 76 μeV for the chopper at the same distance and the window of ± 15 μeV presently available on the backscattering spectrometer at Grenoble.

Crystal Frequency (Hz)	Energy Window (μeV)		
	Crystal		Chopper
	Peak Centre	Leading Edge	
25	290	409	40
50	415	567	76
75	494	692	112
100	574	798	158

Table 3 The energy windows transmitted by a chopper and a rotating crystal assembly for the conditions given in table 1.

This energy window does not exceed the overlap value for 40 metres which is ∿ 1 meV at 6.28Å.

4.3 The scan time

For a frequency of 50 Hz a burst time of 12 μ sec can be achieved by the choice of appropriate values of the collimation and mosaic spread. As an example by setting $\alpha_1 = \alpha_2 = \beta \equiv \alpha$ equation 3 reduces to

$$\Delta t_c = \frac{\alpha}{\sqrt{2}\omega}$$

and the value of the collimation and the crystal mosaic spread required for a burst time of 12 μsec is 18.3 minutes of arc which is acceptable.

5. Conclusions

Our assessment indicates that the selected wavelength band can be substantially increased and the source pulse significantly shortened by the use of a rotating crystal pulse shaper instead of a mechanical chopper. This method has applications in the design of high resolution cold neutron spectrometers and diffractometers on accelerator based pulsed neutron sources. It could also have applications for pulse shortening on pulsed reactors [8] and quasi-pulsed accelerator based neutron sources [9] where the intrinsically long pulse widths limit the resolution capabilities of the source. The concept is presently being tested experimentally [10] at the KENS pulsed neutron source in Japan.

The ultimate pulse shortening device would be represented by a crystal with a time varying angular velocity such that its trace in λ-t space would be a saw-tooth. This seems to be a practical possibility in view of the modest frequency requirements for a uniformly rotating crystal.

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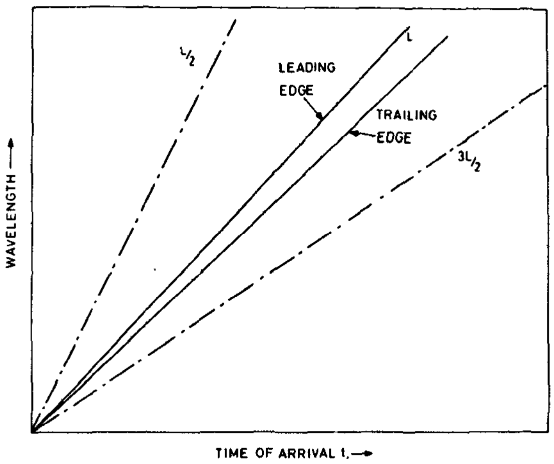


Fig. 1

The λ-t representation of a pulse from a pulsed neutron source at a given distance L from the moderator. At nearer or farther points the λ-t trace has a higher or lower gradient respectively as shown by the dashed lines.

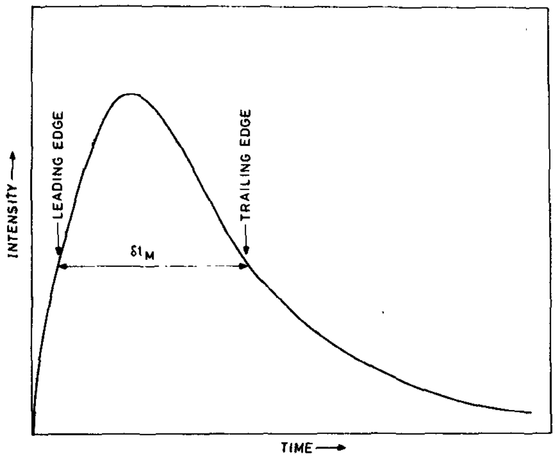


Fig. 2

A schematic representation of the time distribution of a particular wavelength emitted from the moderator. Once formed this distribution remains unchanged as the neutron pulse drifts from the moderator.

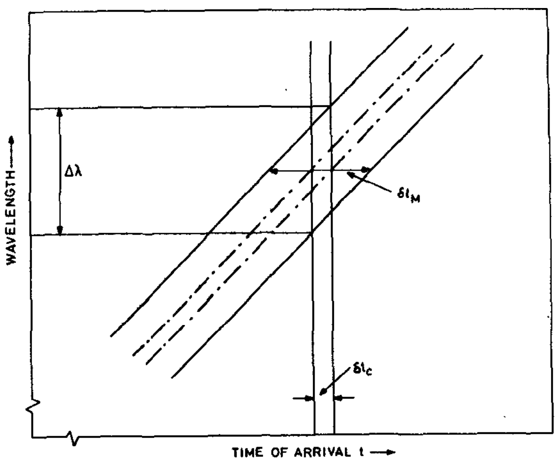


Fig. 3

A relatively narrow wavelength range in a neutron pulse where the leading and trailing edges are approximately parallel. A chopper of burst time δt_c much less than the moderator pulse width δt_M selects a restricted range of wavelengths Δλ from the pulse. An idealised short time cut from the pulse is shown by the dashed lines.

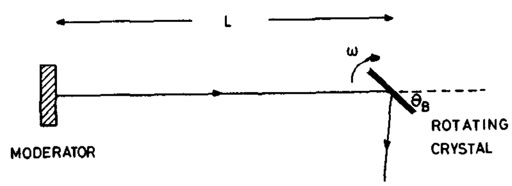


Fig. 4

A rotating crystal shaper at a distance L from the moderator and rotating with constant angular velocity.

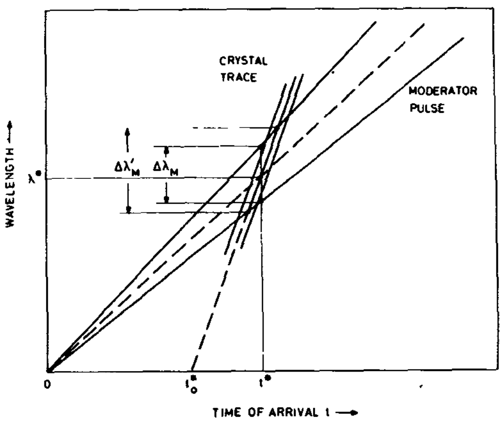


Fig. 5

The principle of operation of the rotating crystal pulse shaper. The crystal is phased such that at a time t* after the poly-chromatic pulse has left the moderator its trace in λ-t space is tangential to the neutron pulse at the desired wavelength. λ*. The maximum wavelength reflected by the crystal at a Bragg angle of 90° is twice the lattice spacing 2d.

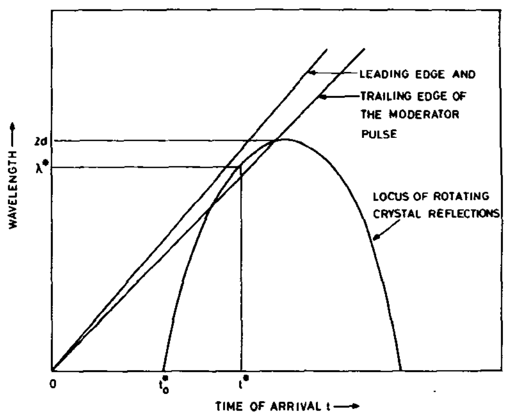


Fig. 6. The general case of the interaction of the rotating crystal pulse shaper with the moderator pulse in which the traces in λ-t space intersect.

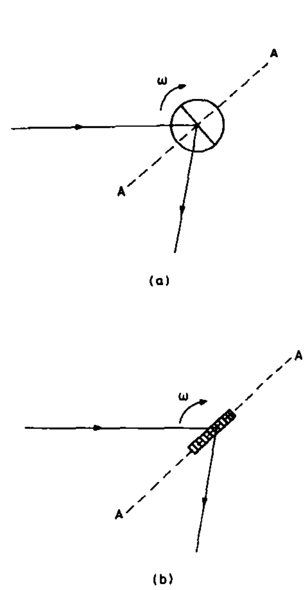


Fig. 7. (a) A cylindrical crystal rotating in a neutron beam. Plane AA, parallel to the scattering vector and passing through the axis of rotation, is unaffected by the Doppler effect. (b) A plate crystal in Laue transmission geometry renders the Doppler effect negligible.

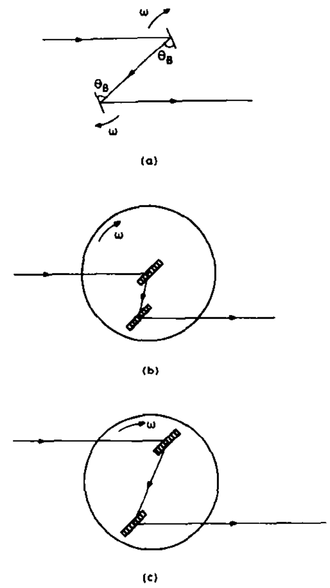


Fig. 8. (a) The use of two rotating crystals to deflect the time-shortened pulse into the drift path of the spectrometer. (b) A method of achieving this by the use of an assembly with a crystal mounted on the axis of a rotating table and a second crystal mounted eccentrically. (c) As in (b) but with both crystals mounted eccentrically and symmetric with respect to the table axis.

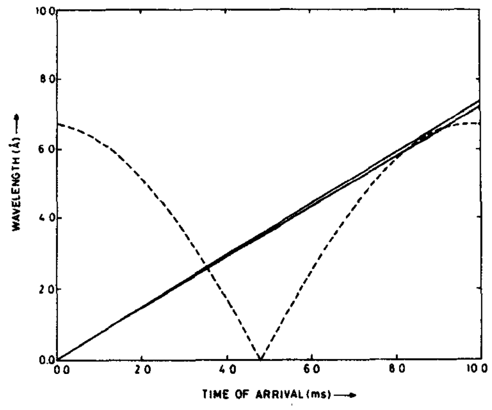
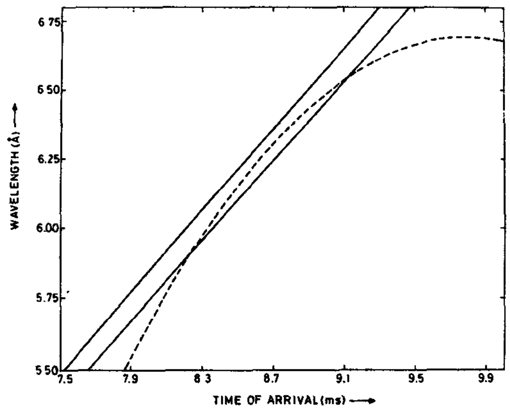


Fig. 9

A graphical solution using a graphite crystal at 5.46 m from the moderator, rotating at 50 Hz and reflecting a wavelength of 6.28Å.



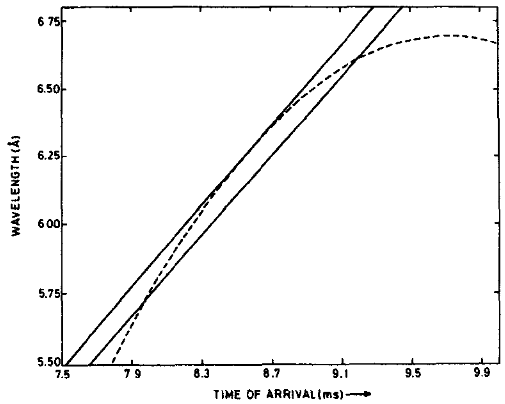


Fig. 10. (a) As for figure 9 but with the wavelength region around 6.28Å.

(b) As for (a) but with the crystal phased to be tangential to the leading edge of the pulse substantially increasing the wavelength band reflected.

Fig. 11

The energy window reflected by a rotating graphite crystal as a function of crystal frequency and distance from the moderator. Separate curves are shown for phasing to the peak maximum and to the leading edge. For comparison purposes the energy band passed by a chopper at the same distances from the moderator as the crystal is shown.