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REMARKS CONCERNING THE EFFICIENCY OF A BOOSTER NEUTRON SOURCE

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ABSTRACT

In the present paper criteria are defined for the comparison of the efficiency of a multiplying booster target with a non-multiplying accelerator target for different injection times and pulse widths. In order to obtain a "symmetric pulse" from the booster, the "Effective Figure of Merit": EFM = 0.75 A, where A stands for the multiplication of the booster. It is shown that for solid state physics scattering experiments using impinging neutrons in the energy range of $0.05 \leqslant E \leqslant 10$ eV, there exists a lower limit of one μsec for the pulse width and therefore a booster target with an amplification of A = 10, a generation time $\tau = 0.02$ μsec, has a "Figure of Merit": FM = 10 and for "symmetric pulses" an EFM = 7.5. For the epi-thermal energy region, an optimum slowing down flux is achieved for an effective water moderator thickness of 28 mm resulting in an energy dependent moderator pulse width: $\Delta t \cong 2/\sqrt{E}$ (μsec, E in eV). If the booster pulse is matched to the moderator response function, then the accelerator injection time $t_0 \cong \frac{1}{2}\Delta t$. This leads to an energy dependent figure of merit: FM(E), that is rapidly decreasing with energy and equal to one at 50 eV.

I. INTRODUCTION

The first powerful booster target has been constructed and operated by Pool[1] at Harwell. It was and it is used for neutron cross section work in the epithermal neutron energy range. In neutron "Time Of Flight" (TOF) experiments, the "Figure Of Merit" (FM)[2-8] is given by

$$FM = \frac{\int_0^\infty \phi(t)dt}{\sigma^n} \tag{1}$$

where σ^2 is the variance of the neutron pulse and given by

$$\sigma^2 = \frac{\int_0^\infty t^2 \phi(t)dt}{\int_0^\infty \phi(t)dt}. \tag{2}$$

In equation (1), "n" may vary[8,9] as

$$0 \leqslant n \leqslant 4. \tag{3}$$

For a simple transmission experiment and also for some scattering experiments, the figure of merit is given by

$$FM = \frac{\int_0^\infty \phi(t)dt}{\sigma^2}. \tag{4}$$

In the following considerations we limit ourselves to that definition of the figure of merit to be used to characterize the efficiency of a booster target.

II. COMPARISON OF THE EFFICIENCY OF A MULTIPLYING BOOSTER TARGET COMPARED TO A NON-MULTIPLYING ACCELERATOR TARGET

If ϕ_0 (n/sec) is the accelerator neutron source strength without multiplication, the neutron source strength of the booster target changes per unit time as follows[10]:

$$\frac{d\phi_B}{dt} = -\lambda\phi_B + \frac{\phi_0}{\tau} \tag{5}$$

where the decay constant is given by

$$\lambda = \frac{|\epsilon|}{\tau} = \frac{k(1-\beta)-1}{\tau} = \frac{1}{\tau A} \tag{6}$$

and where $A = \frac{1}{|\epsilon|}$ is the amplification, τ the generation time, the time between consecutive fissions, k is the multiplication factor and β the delayed neutron fraction in the booster target.
From equation (5) and (6) follows

$$\phi_B(t) = A\phi_0 + (1-A)\phi_0 e^{-\frac{t}{\tau A}} \tag{7}$$

In Fig. 1 the pulse shape is shown for a booster target pulse with amplification of 10 and different injection times $X = \frac{t_0}{\tau} = 1, 6, 10$ and ∞, where t_0 is the injection time in units of τ, the generation time. The figure of merit of the booster pulse compared to the respective accelerator input pulse is given by:

$$FM = FM(A, \tau_0, t_0) = \frac{FM\ (\text{Booster})}{FM\ (\text{Accelerator})} = \tag{8}$$

$$= \frac{[\int_0^\infty \phi_B(t)dt]^2 / \int_0^\infty t^2 \phi_B(t)dt \quad \text{Booster}}{[\int_0^{t_0} \phi_{Ac}(t)dt]^2 / \int_0^{t_0} t^2 \phi_{Ac}(t)dt \quad \text{Accelerator}}$$

$$FM(A, \tau, t_0) = \frac{A^2}{A - 3(1-A)e^{-\frac{X}{A}}\left(\frac{A}{X} + \frac{2A^2}{X^2}\right) + \frac{6A^3}{X^3}}$$

where $X = \frac{t_0}{\tau}$. This figure of merit, FM, has been plotted in Figs. 2 and 3 for an amplification of 5 and 10 respectively. Note that the injection time t_0/τ has to be 5 and 7 correspondingly in order to obtain the same performance characteristic as the accelerator itself. Only for longer injection times the maximum value of 5 and 10 can be reached.

III. THE "SYMMETRIC PULSE SHAPE CONDITION" FOR THE BOOSTER PULSE

For a number of reasons it is desirable to have a "symmetric pulse shape" also for the booster pulse. In order to achieve that we have to request that

$$\sigma_1^2 \equiv \sigma_2^2 \tag{9}$$

where

$$\sigma_1^2 = \frac{\int_0^{t_0} t^2 \phi_B(t)dt}{\int_0^{t_0} \phi_B(t)dt} \tag{10}$$

and

$$\sigma_2^2 = \frac{\int_{t-t_0}^{\infty} (t-t_0)^2 \phi_B(t_0) e^{-\lambda(t-t_0)} dt}{\int_{t-t_0}^{\infty} \phi_B(t_0) e^{-\lambda(t-t_0)} dt} \tag{11}$$

for $t \geqslant t_0$, as indicated in Fig. 4.

From equations (9), (10) and (11) follows

$$y = \frac{X^2}{3A} - (1-A)e^{-\frac{X}{A}} [\frac{X}{A} + 2] - 2A \overset{!}{=} 0 \tag{12}$$

From equation (12) and (8) follows the "Effective Figure of Merit (EFM)" which is plotted as a function of A in Fig. 5. It turns out that the EFM for a symmetric pulse shape is given approximately by

$$\text{EFM} \cong 0.75 \cdot A = 0.75 \text{ FM (maximum)}. \tag{13}$$

IV. THE ADVANTAGES OF A BOOSTER TARGET FOR NEUTRON SCATTERING EXPERIMENTS

For very general reasons such as intensity, moderator-, sample- and detector thickness, we have to match the time- and length of flight path resolution[10,11].

$$\frac{\Delta t}{t} = \frac{\Delta t}{\ell} v \equiv \frac{\Delta \ell}{\ell} \approx \frac{4 \times 10^{-2}}{40} = 10^{-3} \tag{14}$$

or

$$\Delta t \cong 10^{-6} \text{ sec} \tag{15}$$

where Δt is the full width at half maximum of the neutron pulse, t the flight time of neutrons with velocity v over a flight path of length ℓ and $\Delta \ell$ is its uncertainty.

Therefore, one μsec pulses are a lower limit in neutron scattering experiments. Considering a booster target with multiplication 10, we obtain according to Fig. 3 for a "symmetric pulse shape" an injection time of $t_0 \cong 22\tau$. Booster targets with a generation time of $\tau \cong 0.02$ μsec can be built leading to an injection time $t_0 \approx 0.5$ μsec and an effective multiplication of 7.5. The booster pulse shape is well matched with the moderator response function of heterogenously poisened moderators[7-11] and neutron energies $E_n \leqslant 10$ eV.

V. THE BOOSTER EFFICIENCY IN THE Epi-THERMAL ENERGY REGION

It has been shown[2-5,7-10] that for epithermal neutrons an optimum slowing down flux is obtained for an effective moderator thickness of 2.8 cm resulting in an energy dependent moderator pulse width of

$$\Delta t = \frac{d}{v} \cong \frac{2}{\sqrt{E}} \quad (\mu\text{sec}) \tag{16}$$

where the neutron energy is given in eV.
If we want to match the accelerator booster pulse with the response function of the moderator then the accelerator injection time t_0 ought to be

$$t_0 \cong \tfrac{1}{2}\Delta t = \frac{1}{\sqrt{E}} \quad (\mu\text{sec}) \tag{17}$$

or for

$$X = \frac{t_0}{\tau} = \frac{1}{\tau\sqrt{E}} \tag{18}$$

Using equation (8), the energy dependent Figure of Merit has been calculated for an amplification A = 10 and a neutron generation time $\tau = 20$ nanosec and the results are plotted in Fig. 6. As we can see from Fig. 6, the booster is only useful for neutron energies below about 50 eV. Around 10 eV, the FM ≈ 5. Therefore the use of booster targets in the epi-thermal energy range is rather limited. The best use of booster targets can be made for solid state physic scattering experiments using impinging neutrons with energies below 10 eV where the maximum Figure of Merit can be obtained.

VI. LITERATURE

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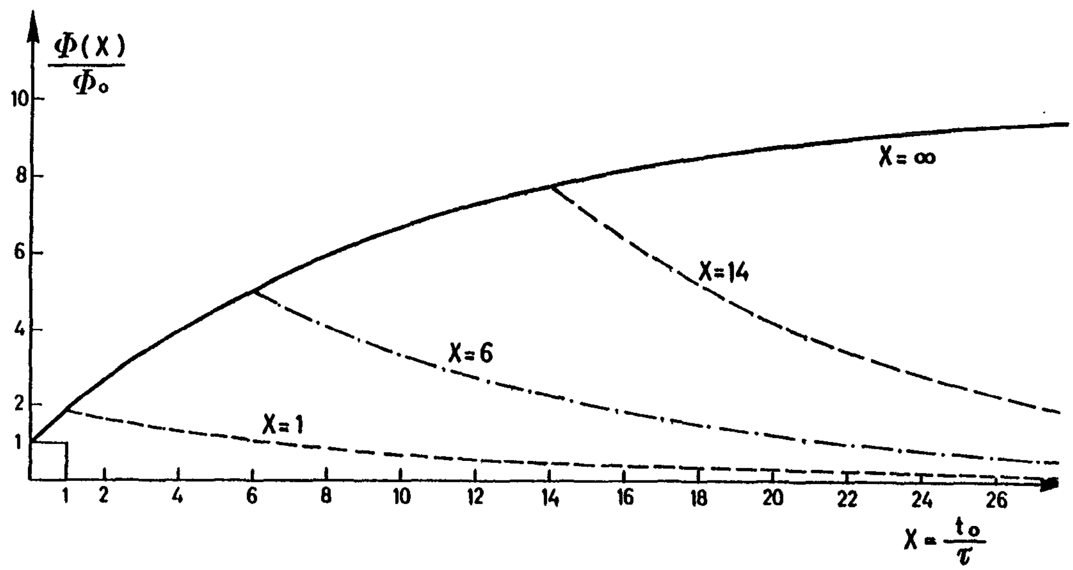

Fig. 1 - Pulseshape of a boosterpulse with amplification 10 and different injection times $X = \frac{t_0}{\tau} = 1, 6, 10$ and ∞

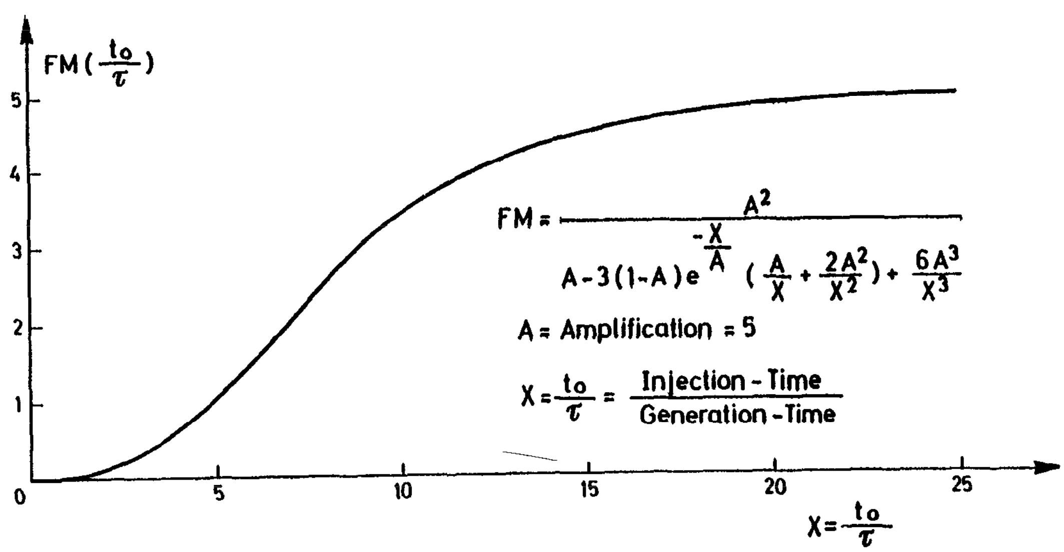

Fig. 2 - Figure of Merit for a Booster target with Amplification of 5

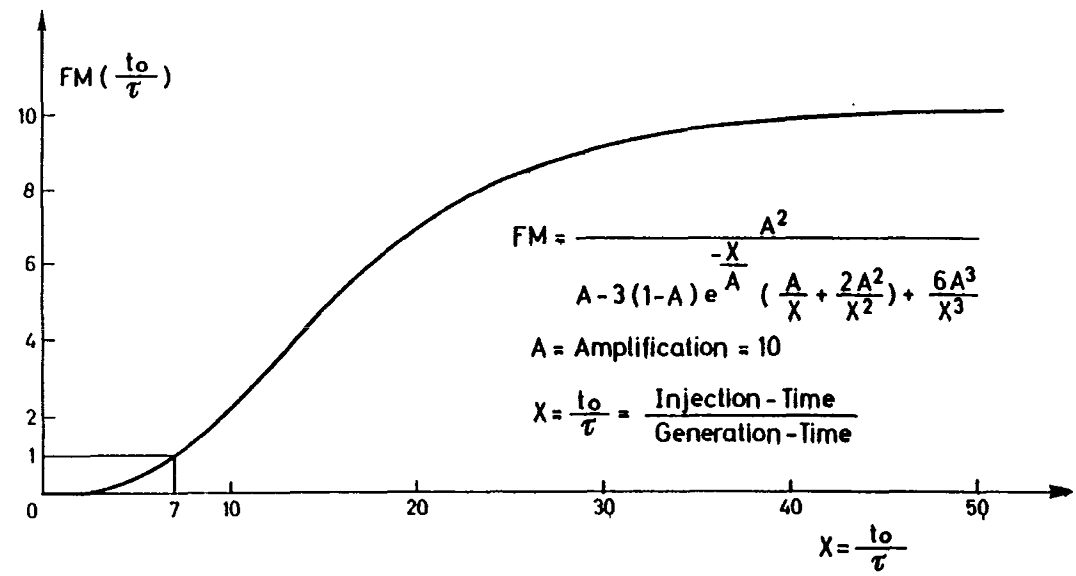

Fig. 3 - Figure of Merit for a Booster target with Amplification of 10

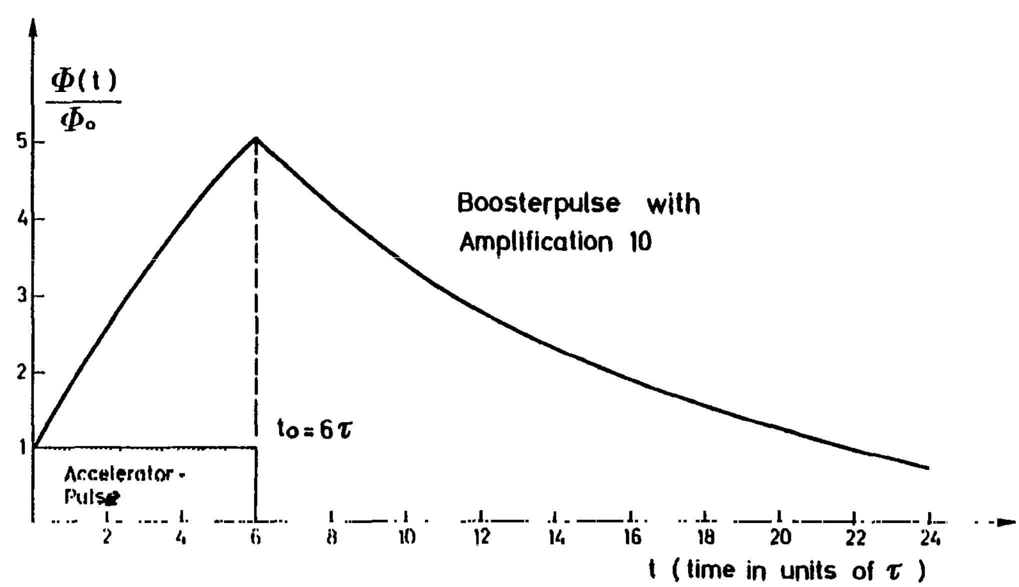

Fig. 4 - Boosterpulse for Amplification of 10 and Injection time : $t_o = 6\tau$

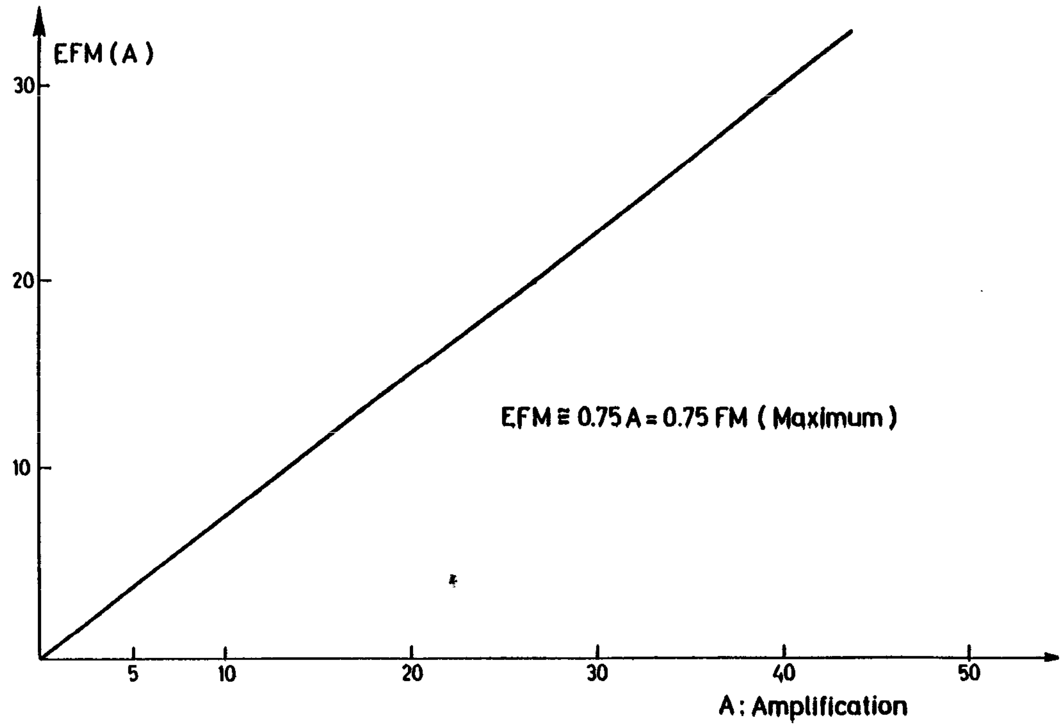

Fig. 5 = The Effective Figure of Merit for Symmetric Pulse-Shape

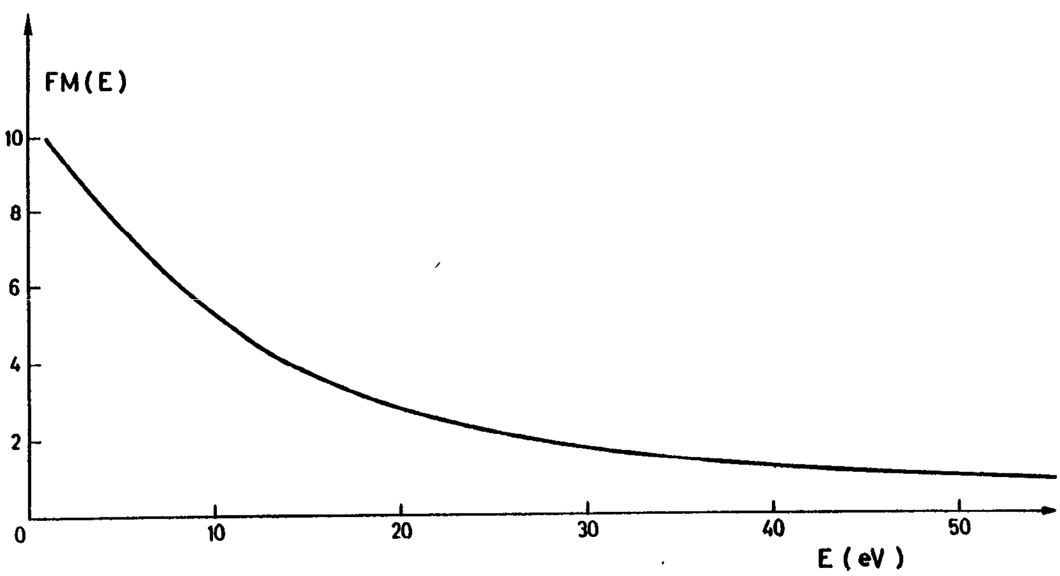

Fig. 6 - Figure of Merit for a Booster target as Function of Neutron energy with Amplification of 10 and generation time $\tau = 0.02\ \mu sec$