Longer Pulse Length by a Vibrating Target

in the CERN Synchro-Cyclotron

by

B. Hedin
CERN, Genève, 1961

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The normally low duty ratio of a synchro-cyclotron is a disadvantage for many counter experiments. At the CERN synchro-cyclotron the pulse length for secondary beams from an internal target (at half peak intensity) is 150 to 200 μsec. As the repetition time is 18 msec the duty ratio is about 1% (or 0.3% if RF structure is considered).

Several methods have been proposed and used to lengthen the pulses:

1. Suitable modulation programme, with a low rate of change of frequency when the beam reaches the target or the extraction radius.

A slight improvement is very easy to arrange with the CERN vibrating modulator, as only a small reduction of the amplitude is required to get the extraction close to the moment of maximum capacity. Where a rotating modulator is used and has larger capacity than required some improvement can be achieved by shaping the condenser blades (1). The scope for improvement is limited as still the same times are required to reduce capacity to minimum and for the acceleration.
2. Separate RF programme for extraction

If the main RF programme is stopped just before the first protons reach the target all the protons will continue to circulate at a small range of radii for a considerable time. If a RF voltage of proper frequency is applied to a C-shaped electrode around the orbits some protons will be accelerated others decelerated. With noise modulation the protons would gradually be equally distributed over the range of radii corresponding to the band width provided no protons got lost. In the presence of a target or extraction system and proper modulation programme one may obtain a pulse of a length up to the end of next cycle of the main RF programme, that is an essentially continuous beam. A loss of intensity (of about 50%) seems difficult to avoid (2, 4).

3. By a very small target the number of traversals can be increased to large numbers. Simultaneously the probability for a hit on any one turn of a proton is reduced. If, therefore, the RF programme is switched off when the protons have reached the proper radius they will be only slowly "absorbed" by the target. Some loss of intensity is unavoidable as a small target is less effective than a thick target. Under a certain size however the number of multiple traversals multiplied with the target thickness is constant. The calculated equivalent target thickness at radius 226 cm for the CERN-SC 0,5 is radiation lengths (≈ 10 mm Cu or 250 mm Be). With the normally used 50 mm Be target the equivalent target thickness is 50% larger. At radius 220 cm the ratio is 2.5 to 3.

With a very small target the cooling will be entirely by radiation, limiting the choice of materials to those that
can stand high temperatures. Tests have been done with a 1 mm$^3$ carbon target supported by a 8 micron diameter tungsten wire at radius 220 cm. As carbon is a less effective target material than beryllium (less g/cm$^2$ per radiation length) it was not surprising that the average intensity was down a factor 6. The pulse length (counts per pulse / peak counting rate) was 880 /usec to be compared with 180 /usec for the normal target. With a still smaller target it is likely that the duty ratio should improve further without any more loss in intensity. The prospects do not however look very interesting.

4. With a vibrating target

If as in methods 2 and 3 the RF is switched off when a desired radius is reached the protons will continue to circulate at this radius for a considerable time, depending on the gas pressure and on the radius. At $R > 223$ cm particles get lost through large radial oscillations. If a target is moved slowly into the circulating beam a long pulse of secondary particles will result. This method was proposed at CERN by G. Fidecaro and A.W. Merrison. It was first realized at the Nevis Cyclotron by J. Rosen (3).

The method used by J. Rosen and also adopted at CERN consists of a vibrating target driven by a moving coil in synchronism with the modulation frequency. The main problem is to get a reliable mechanism for the drive and this problem will be analysed.

The appearance of the target is shown in fig. 1 and the notations used are indicated in fig. 2. The elasticity
of the arm supporting the target cannot be neglected. Although in reality it is a distributed elasticity it will in the interest of simplicity be considered as concentrated at distance \( b_2 \) from the target end of the arm of length \( b(v) \). The springiness of the arm is \( S_2 \) radians per Neutronmeter (M.K.S. units are used throughout), that of the support \( S_1 \) (rad/Nm). The inertia of the coil and the nearest part of the arm is \( J_1 \) (kgm\(^2\)) with respect to the centre of gravity of the whole system, that of the target \( J_2 \) (kgm\(^2\)) with respect to the flexing point at distance \( b_2 \). As all motions take place in the almost homogeneous magnetic field \( B \) about 1.8 (\( \text{Wb/m}^2 \)) of the cyclotron induced eddy currents are opposing the motion: \( D_1 \) (Nms/rad) for the coil-former, \( D_2 \) (Nms/rad) for the outer part of arm. The area of the coil is \( A \) (m\(^2\)), number of turns \( N \), resistance \( R \) (\( \Omega \)) and inductance \( L \) (Henry).

Only sinusoidal motions are considered.

The target motion is \( y = y_0 \sin \omega t \)

The coil angle is \( \varphi = \varphi_0 \sin (\omega t + \alpha) \)

The frequency is \( \omega = 2\pi f \)

\( \alpha \) is the phase angle between the systems.

One gets the following equations:

\[
\begin{align*}
0 &= \frac{y - \varphi}{S_2} + D_2 \frac{dy}{dt} + J_2 \frac{d^2y}{dt^2} \\
NABi &= \frac{\varphi}{S_1} + \frac{1}{S_2} \left( \frac{b}{b_2} \right)^2 (\varphi - y/v) + D_1 \frac{d\varphi}{dt} + J_1 \frac{d^2\varphi}{dt^2}
\end{align*}
\]
With current in coil \( i = i_1 \sin \omega t + i_2 \cos \omega t \)
and induced voltage \( U = U_1 \sin \omega t + U_2 \cos \omega t \)

One finds:

\[
\tan \alpha = \frac{\omega S_2 D_2}{1 - \omega^2 S_2 J_2}
\]

\[
U_1 = -NAB \omega^2 \frac{y_0}{\ell} S_2 D_2
\]

\[
U_2 = NAB \omega \frac{y_0}{\ell} (1 - \omega^2 S_2 J_2)
\]

\[
\frac{S_1 \ell}{y_0} \cdot NABI_1 = 1 - \omega^2 \left[ S_1 J_1 + S_1 J_2 \left( \frac{\ell}{\ell_2} \right)^2 + S_2 J_2 + S_1 D_1 S_2 D_2 \right] + \omega^4 S_1 J_1 S_2 J_2
\]

\[
\frac{S_1 \ell}{y_0} \cdot NABI_2 = \omega \left[ S_1 D_1 + S_1 D_2 \left( \frac{\ell}{\ell_2} \right)^2 + S_2 D_2 \right] - \omega^3 \left[ S_1 D_1 S_2 J_2 + S_1 J_1 S_2 D_2 \right]
\]

The voltage at the terminals of the coil is then:

\[
V = V_1 \sin \omega t + V_2 \cos \omega t \text{ with}
\]

\[
V_1 = U_1 + R i_1 - \omega L i_2,
\]

\[
V_2 = U_2 + R i_2 + \omega L i_1
\]

If eddy current losses are small, \( U_1 \approx 0 \)

\( i_2 \approx 0 \)

\[
U = U_2 = NAB \frac{y_0}{\ell} \cdot 2 \pi f \left[ 1 - \left( \frac{f}{f_2} \right)^2 \right]
\]

\[
NABI_1 = \left[ 1 - \left( \frac{f}{f_1} \right)^2 \right] \left[ 1 - \left( \frac{f}{f_3} \right)^2 \right] \frac{y_0}{\ell S_1}
\]
\[ f_1 = \frac{1}{2} \pi \sqrt{S_1 J_1 + S_1 J_2 \left( \frac{l_1}{l_2} \right)^2 + S_2 J_2} \]

\[ f_2 = \frac{1}{2} \pi \sqrt{S_2 J_2} \]

\[ f_3 = f_2 \sqrt{1 + J_2/J_1} \]

The drive current would be zero at frequencies \( f_1 \) and \( f_3 \). To make \( f_1 \) equal the operating frequency a strong spring, low \( S_1 \), would be required at the support. For the fine adjustment of the target vertical position and to bring target down when not in use superimposed dc current is used. Very strong dc current would be required in this case.

If \( f_3 \) is to be made equal to the operating frequency a rather flexible arm (fatigue problems!) is required. The required amplitude of vibration of the coil is increased in the ratio \( J_2/J_1 \). If this ratio is small the two resonant frequencies \( f_2 \) and \( f_3 \) are close and the amplitude of the target motion will depend strongly on small variation in resonant frequency \( f_1 \), due to heating up. If the ratio \( J_2/J_1 \) is large the coil will swing over large angles where the equations are no more valid. A compromise might be found between the extremes. (An example is calculated as type 5 in Table 1).

The arrangement adopted however is to use a rather stiff arm with a resonant frequency \( f_2 = 130 \) c/s considerably higher than the drive frequency \( f = 54 \) c/s. In order to reduce the power the mass and inertia of every moving part are made as low as thought compatible with a reliable operation.

The choice of the most suitable size of coil can best be seen if \( S_1 \) large, \( S_2 = 0 \) and \( \frac{l_1}{l_2} = 1 \). Then
\[ P = \frac{1}{2} R i_1^2 = \frac{R}{2} \left( \frac{\omega^2 J_1 + J_2}{(NAB)^2} \right) \left( \frac{y_0}{l} \right)^2 \]

If the size of the coil is changed with the linear scale \( K \)

\[ R \rightarrow R_0 \cdot K^{-1} \]
\[ J_1 \rightarrow J_{10} \cdot K^5 \]
\[ A \rightarrow A_0 K^2 \]

By optimising for power one finds \( J_{1\text{opt}} = J_2 \).

The temperature difference within the winding is proportional to the power-density and to the square of the linear dimensions that is to \( P/K \). By optimising for temperature one finds \( J_{1\text{opt}} = 1.5 J_2 \).

One can also compare windings of copper and aluminium wire with densities 8900 resp. 2700 kg/m\(^3\) and resistivities \( 1.72 \cdot 10^{-8} \) resp. \( 2.72 \cdot 10^{-8} \) Ω m. If the entire mass of the coil were in the conductor the optimal size aluminium coil should be larger by a factor \( K = 5 \frac{\sqrt{8900}}{\sqrt{2700}} = 1.27 \). The current would then be smaller by a factor \((1.27)^2\), the resistance with aluminium coil larger by a factor \( \frac{2.72}{1.27 \cdot 1.72} = 1.25 \) and the power ratio \( \frac{1.25}{(1.27)^4} = 0.48 \) in favour of aluminium.
However considering that the weight of the insulation and the coil former also gets larger for aluminium the advantage of aluminium conductor decreases. If with aluminium conductor one has to add equal weight for insulation and former one gets the optimum size ratio \( \frac{5}{\sqrt{2900 + 2700}} / \sqrt{2700 + 2700} = 1.166 \), the current ratio \((1.166)^{-2}\) and the power ratio aluminium to copper:

\[
\frac{2.72}{1.72} \cdot \frac{1}{1.166} \cdot \frac{1}{(1.166)^4} = 0.74
\]

The power in itself is no particular problem but the over-temperature inside the winding for equally shaped coils is proportional to the power and sets a limit on the amplitude of vibration that can be used.

The most favourable coil from inertia point of view is a rectangular one turning around its long axis. A round coil, as used, can be wound more simply and gives a more even heat distribution in the winding under hard operating conditions.

Data for some vibrating targets are tabulated in Table 1. The type actually used May 1961 is No. 3.

As the coil has to work in vacuum the cooling presents some problems. Some heat can be conducted away by a heat sink, consisting of a number of copper strips between the coil former and the base. For the execution used at CERN 10 copper strips \((30 \times 0.2 \text{ mm}^2)\) are used. Radiation of heat also contributes to the cooling, particularly if the coil and arm are painted black. The following results are achieved for coil type 1:
Temperature of coil  |  120°C  |  170°C  
Conducted heat     |  23.7W  |  35.5W  
Radiated heat      |  9.5W   |  17.9W  
Total power        |  33.2W  |  53.4W  

In order to get an acceptable long life of the coil the temperature should not exceed 120°C. Particularly harmful seems to be repeated heating and cooling of the coil as the surface of the araldite used cracks under the uneven heat distribution then prevailing.

The feeding wires to the coil are apart from the motion of the terminals on the coil also subject to the force from the magnetic field. For a long wire one gets a vibration amplitude

\[ X_v = \frac{B \cdot I_0}{a \cdot \gamma} \]

where \( a \cdot \gamma \) is the weight in kg/m of the wire. For a 0.1 mm² Cu wire with 1 A and 1.8 Wb/m² one gets about 20 mm amplitude. Such a vibration gives a considerable extra strain at the two fixing points of the wire. To reduce the strain one can use twisted pairs of wires with common insulation so that the forces from the current to and from the coil compensate each other. Also with sufficiently heavy multistranded single wires an acceptable life can be achieved.

The vibrating target has to be driven in synchronism with the modulation of the RF voltage of the synchro cyclotron and in such a phase that it is in its most downward position when the protons arrive at the target radius. Protons with large vertical oscillation amplitude might still hit the target in this position and produce an immediate short burst of secondary particles. The RF should be pulsed off in this very moment.
The practical arrangement used is that two targets are in the cyclotron tank. For the drive one 30 W amplifier (2 tubes E150L) is used with the input taken over adjustable phase shifter and preamplifier from the tuning fork modulator drive circuit. From the cyclotron control room one or the other (or no) target can be connected and the amplitude and position adjusted. The target not in use gets d.c. current to move it down out of the beam, although that should not be necessary as in the latest model of vibrating targets the rest position, if a wire breaks, is below the dee level.

For much higher modulation frequencies a reliable vibrating target of sufficient amplitude and size seems very difficult to realize. In the Liverpool synchro-cyclotron a rotating device is used with 6 targets driven at the same speed as the rotating condenser, 1000 rpm. Considering the problems of bearings and cooling it seems to be better to use a vibrating target up to about 60 c/sec.

When the target moves upwards it intersects more and more of the coasting protons until all the beam should be absorbed by the target in its most upward position. With a repetition time of 18 msec (54 c/s) the total length of the long pulse would be nearly 9 msec with the centre 5 to 7 msec after the immediate burst, that is when the target has a high speed of motion upwards and the density of protons is also high.

The observed pulse shape in a typical case is shown in fig. 3. Time zero is the moment when the modulator has minimum capacity. At about 6.3 msec the frequency is 17.25 Mc/s and the beam has reached the target radius. A short pulse of about 150 μsec
half width appears. From 9 to 16 msec the long pulse comes out. If the amplitude of the target is rather small some protons are not hitting the target until the RF voltage again goes on about 1 msec after the start of next cycle and when a frequency of about 26 Mc/s is passed. This is due to the perturbation of the orbits caused, rather than real acceleration.

The intensity in the pre-pulse can be reduced by increasing the amplitude of the target vibration and lowering its mean position. To avoid the pre-pulse entirely the target tip must be below the edge of the dee, 6 cm below the midplane. It is however sufficient to ensure that the peak counting rate of the pre-pulse is lower than that of the long pulse. This can be achieved already with about 1.5 cm amplitude, without loss of intensity. Then also the after-pulses at 1 (= 19) and 3 (= 21) milliseconds disappear. When required a gating of the counters can be arranged to accept only the long pulses. The pre-pulse can also be practically eliminated by a beam chopper, that on a small radius stops protons with large vertical amplitude. The reduction in intensity is very small.

A limitation for the use of a vibrating or rotating target is the radius that can be used. As the beam has to circulate at the target radius and has a certain amplitude of radial oscillations, in our case about 8 cm, there must be no obstacle for the beam over that amplitude. For the CERN synchro-cyclotron n = 0.2 is at radius 227 cm. The radius normally used for fixed targets is 226 cm. The inside of the channel wall for extracted proton beam is at radius 228 cm, which means that the maximum vibrating target radius without loss of beam is 220 cm. If the target is placed at 223 cm about 30% of the intensity is lost.
Another limitation is exactly that the target is moving. This means that perfect beam optics cannot be realized. In the case of $\mu$-meson beams this is of no importance as the equivalent source for the $\mu$-mesons in any case is quite large.

The main advantages of the vibrating target method to get a long pulse are its simplicity and its high efficiency. Under certain circumstances also the fact that the RF-structure of the beam is non-existing can be counted in favour. This has not yet been experimentally verified but can be taken for granted considering the energy spread of the protons (about 1%) and the large number of revolutions (about $3 \cdot 10^4$) between the RF stop and the beginning of the long pulse.

An interesting use of the vibrating target is to produce single bursts for a bubble chamber. The cyclotron is running normally for a counter experiment with full frequency range and a fixed target at radius 226 cm. By applying a positive pulse immediately followed by a negative pulse the vibrating target can be brought up in the median plane for just one beam pulse, to be used for the bubble chamber. With practically no loss of intensity the cyclotron can in this way be used for two experiments simultaneously operating off two different targets.

I am grateful for the valuable assistance of many of the staff at CERN, in particular Messrs Beger, Blythe, Citron, Francia, de Groot, Heintze, Michaelis and Rubbia. I would also like to express my gratitude for the encouragement from Prof. P. Preiswerk and Dr. P. Lepoutre.
<table>
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<th>Type</th>
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<tr>
<td><strong>Coil Data:</strong></td>
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<tr>
<td>Material (diameter mm) &amp; 1</td>
<td>Cu(0.5) &amp; Al(0.5) &amp; Cu(0.5) &amp; Cu(1) &amp; Cu(1)</td>
</tr>
<tr>
<td>Turns &amp; N</td>
<td>500 &amp; 700 &amp; 700 &amp; 432 &amp; 432</td>
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<tr>
<td>Area &amp; A</td>
<td>2.10 &amp; 2.34 &amp; 2.34 &amp; 4.10 &amp; 4.10</td>
</tr>
<tr>
<td>Inertia &amp; J</td>
<td>1.60 &amp; 0.89 &amp; 2.00 &amp; 6.10 &amp; 6.10</td>
</tr>
<tr>
<td>Damping &amp; D</td>
<td>1.8 &amp; 1.8 &amp; 1.8 &amp; 9.6 &amp; 9.6</td>
</tr>
<tr>
<td>Resistance &amp; R</td>
<td>9.4 &amp; 22.4 &amp; 14.0 &amp; 2.83 &amp; 2.83</td>
</tr>
<tr>
<td>Inductance &amp; L</td>
<td>5.0 &amp; 10 &amp; 10 &amp; 5.3 &amp; 5.3</td>
</tr>
</tbody>
</table>

| **Arm Data:** |        |
| Springiness & S | 1.85 & 3.8 & 3.8 & 3.8 & 31.0 |
| Inertia & J | 8.10 & 5.1 & 5.1 & 5.1 & 5.1 |
| Damping & D | 20 & 2.5 & 2.5 & 2.5 & 2.5 |

**Drive Data (54 c/s, 2 cm peak-peak):**

| i (RMS) & A | 1.80 & 0.71 & 0.81 & 1.11 & 0.04 |
| V (RMS) & V | 22.8 & 27.5 & 24.7 & 24.8 & 28.0 |
| P = V·i & VA | 41.0 & 19.5 & 20.0 & 27.5 & 1.12 |
| P & W | 32.6 & 11.5 & 9.7 & 4.4 & 1.02 |

sc/1862/a1
Litterature


VIBRATING TARGET PULSE

FIG. 3

- RF on
  - 26.1 Mc/s
  - 29.1 Mc/s

- RF off
  - 17.25 Mc/s
  - 28.0 Mc/s
  - 26.1 Mc/s
  - 17.25 Mc/s