Q-MEASUREMENT IN THE SPS

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Part One  System Description and Specification
Part Two  Technical Description  a) Beam excitation
          b) Pickup and amplifier
          c) Frequency Measurement

1.1. System Description

This note proposes a system for measuring the Q-value in the SPS. The working value of Q is expected to be between 27 and 28, and is to be measured to an accuracy of \(10^{-3}\) in both the vertical and horizontal planes. Three measurements are required per machine cycle at intervals of 200 msec minimum.

The automatic digital measurement of the betatron frequency of the ISR has been described by Hansen¹) and a modification of this method is suitable for use in the SPS. Betatron oscillations are excited on the beam by a deflector magnet and free oscillations are coupled out using a standard position monitor. The monitor signal is filtered and its frequency measured using a digital technique.

The proposed measurement system is illustrated by the block diagram.
Betatron oscillations may be excited either during one turn using a fast kicker magnet, or over several turns by a less powerful magnet with a correctly phased current waveform.

It is desirable to use the standard pickup and amplifier for oscillation monitoring, but it is important that the noise contributed by the amplifier is kept to a minimum.

The technique of measuring the betatron frequency depends on how quickly the signal is attenuated by Landau damping. The decay mechanism is strongly affected by synchrotron oscillations, and we have shown elsewhere that if the ratio of the synchrotron frequency to the revolution frequency is greater than half the Q spread, then the damping is not significant in 30 revolutions. The times in the machine cycle when this is satisfied are indicated in the table below by a *. When \( Q_s < \frac{1}{3} \Delta Q \) as for weak trapping or a debunched beam, the betatron signal falls to 37% in \( N = 1/(3\Delta Q) \) revolutions.

<table>
<thead>
<tr>
<th>Energy</th>
<th>Injection</th>
<th>Extraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q_s</td>
<td>.035</td>
<td>.02</td>
</tr>
<tr>
<td>\Delta Q_H</td>
<td>.12</td>
<td>.04</td>
</tr>
<tr>
<td>\Delta Q_V</td>
<td>.024</td>
<td>.012</td>
</tr>
<tr>
<td>( N_H = \frac{1}{3\Delta Q_H} )</td>
<td>2.7</td>
<td>8</td>
</tr>
<tr>
<td>( N_V = \frac{1}{3\Delta Q_V} )</td>
<td>14</td>
<td>*</td>
</tr>
</tbody>
</table>

At extraction we expect the betatron signal to be substantially unattenuated for at least 30 beam revolutions so that the betatron frequency may be measured sufficiently accurately by timing a number of zero transits.
At injection the signals are more heavily damped and if the Q spread is uncorrected a digital processing technique is proposed for measurement of the frequency and its spread.

The timing of the beam deflection and subsequent measurement will be determined by a preset register under program control. The requested Q-value will then be passed to the computer control system.

1.2. Specification for the Q Measurement System

a) Measurements Required

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>range of Q</td>
<td>27-28</td>
</tr>
<tr>
<td>precision</td>
<td>±0.001 - not less than ±0.1ΔQ</td>
</tr>
<tr>
<td>times per cycle</td>
<td>3</td>
</tr>
<tr>
<td>intervals of</td>
<td>200 msec minimum</td>
</tr>
<tr>
<td>beam intensity</td>
<td>$10^{11} - 10^{13}$ ppp</td>
</tr>
</tbody>
</table>

b) Subsystem Performance

Deflector to give a 2.5 mm deflection of the beam with energy from 10 GeV to 400 GeV in less than 20 revolutions.

Pickup, amplifier and filter should have a passband of $0-\frac{1}{2}, \frac{1}{2}-1$ or $1-1\frac{1}{2}$ times $f_r$ (44 kHz) with a -40 dB slot within 1 kHz of $f_r$. It should give a 14 dB S/N ratio in the filter bandwidth for a ± 1 mm deflection at $10^{11}$ ppp.

Frequency measurement should give an accuracy of ± 0.1% $f_r$ if the signal is available at 14 dB S/N for at least 30 beam revolutions. An accuracy of ± 0.1ΔQ $f_r$ should be expected for other conditions.

c) Location of deflector magnets

<table>
<thead>
<tr>
<th>Type</th>
<th>Location</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>BKQH near QF</td>
<td>5-173</td>
</tr>
<tr>
<td>Vertical</td>
<td>BKQH near QD</td>
<td>5-183</td>
</tr>
</tbody>
</table>
d) Cost estimate

Beam deflectors H and V

474 kSF using fast kickers
(or
170 kSF using slow exciters)

Frequency measurement

20 kSF
PART TWO

TECHNICAL DESCRIPTION

Beam Excitation
Pickup and Amplifier
Frequency Measurement

2.1. Excitation of Betatron Oscillations

Modulation of the high energy SPS beam by amounts which are readily detectable requires strong fields with high peak powers. Achieving this is expensive, so the various techniques are considered in more detail.

Commonly used methods of exciting coherent betatron oscillation are:

a) modulation of the r.f. accelerating field
b) applying transverse electric field waveform
c) applying transverse magnetic field waveform.

Modulation of the r.f. has been used with success in several accelerators\(^3,4\), however interference with the r.f. acceleration system is not desirable.

Electric deflection fields are not very effective at 300 GeV; the maximum deflection obtainable from a field \(E\) applied over a length \(l\) is \(\frac{e\lambda E}{\gamma\pi p c^2} \sqrt{\beta_1 \beta_2}\). With say 10 kV applied to plates of \(\frac{1}{2}\) metre length and 10 cm spacing the best deflection is only 0.01 mm. Significantly larger deflections are difficult to obtain using this method.

Magnetic deflection systems are more effective, since \(BxV\) replaces \(E\) in the expression. The 0.01 mm deflection can be obtained magnetically with about 1 gauss over the \(\frac{1}{2}\) metre length. The exact system employed depends on the required rate of rise of field. We look at three possibilities.
a) Fast kick over one turn

A kiloamp current pulse is driven down a ½ metre transmission line straddling the beam, giving rise to the required field of 300 gauss. The pulse has a flat top lasting 23 μsec with rise and fall times of 1 μsec. It is generated by discharging a pulse forming network into the transmission line loop using a thyratron switch.

b) Excitation over many turns

Coherent oscillations are excited over some 10-20 revolutions by a magnetic field driven at the betatron frequency \( f_q = (Q-n)f_r \), (0-22kHz). The exciting field is then removed and the frequency of the free oscillations is measured as before by the counter method.

The required field is conveniently generated by driving the current of order 60 amps peak down a loop straddling the beam. The current drive, which requires about 35 volts peak, may be provided by the power amplifier described in ref. 5.

c) High frequency excitation over many turns

A sinusoidal field of higher frequency may also be used to drive the beam, provided the field phase seen by a bunch slips by \( 2\pi(Q-n) \) for each circuit of the ring. We gain two advantages by working at a higher frequency, firstly the fractional frequency range is smaller and secondly the deflecting loop can be part of a resonant tank circuit. However a high frequency implies a high reaction voltage for the same peak field.

It is convenient to operate at 1.2 MHz (i.e. 27.5 \( \times f_r \)) using a tank Q factor of 20. The Marconi r.f. power amplifier type x 250-1KW provides a suitable driver.

A comparison of the drive methods is made for the horizontal deflection. The required aperture is 153 x 43 mm
giving an inductance of \( L = \frac{u_0wl}{h} = 4.3 \, \text{uH/m}. \) For a deflection of 2.4 mm the fast kicker requires a field of 164 gauss-metre and the slow exciters require a sinusoidal field of 16.4 gauss-metre peak over 20 revolutions. The following drive parameters are required:

<table>
<thead>
<tr>
<th>length</th>
<th>field</th>
<th>max. freq.</th>
<th>tank Q-factor</th>
<th>drive current</th>
<th>max volts</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) 3m</td>
<td>328g</td>
<td>600kHz</td>
<td>matched</td>
<td>1200 amp</td>
<td>1200 v</td>
</tr>
<tr>
<td>b) 1m</td>
<td>+16.4g</td>
<td>22kHz</td>
<td>matched</td>
<td>± 60 amp</td>
<td>± 35 v</td>
</tr>
<tr>
<td>c) 1m</td>
<td>+16.4g</td>
<td>1.2MHz</td>
<td>20</td>
<td>± 3 amp</td>
<td>±1.200 v</td>
</tr>
</tbody>
</table>

2.2. The Deflector Magnet

a) The Fast Kick Method

This method requires a deflector magnet similar in design to the other fast kickers in the 300 GeV machine. The programme of design and construction of these kickers is being undertaken by Faugeras, who has considered the requirements of the deflectors for Q measurement.

Specification

- Rise time: 1 \( \mu \text{sec} \)
- Fall time: 1 \( \mu \text{sec} \)
- Duration: 23 \( \mu \text{sec} \) between \( \frac{1}{2} \) amplitude points
- Deflection: 2.5 mm over whole energy range specified
- Beam energy range: 10-400 GeV
- No times per cycle: 3
- Interval between: 200 \( \mu \text{sec} \)
- Flat top stability: ± 5% max variation on nominal amplitude
- Overshoot: ± 5% max on tail
- Location: Horizontal deflector BKQH near QF at 5-173
- Vertical deflector BKQV near QD at 5-183
The specifications on the shape of the pulse are necessary to limit the transient phase distortions on the free betatron oscillation waveform as seen by a pickup. These phase distortions would prejudice the accuracy of the frequency measurement and a delay of three beam revolutions is made before frequency measurements is started to allow the transients to settle. A clipper switch on the kicker will probably be necessary to ensure that the fall time meets the specification. It is hoped that horizontal and vertical kicker units being developed as prototypes for more stringent systems will meet the requirements of \( Q \) measurement.

b) **Deflector for slow excitation**

The magnet required for the slow excitation method can be of much simpler mechanical design since the peak power levels are very much lower.

The magnet can be constructed outside the vacuum pipe and hence remove the requirement for an auxiliary vacuum system. The vacuum pipe would be made of ceramic to reduce eddy current losses, but metallised internally with longitudinal stripes to allow a low impedance 200 MHz path. The magnet loop would be surrounded by ferrite to define the magnet flux path and to minimise the reluctance.

Thus the deflection system consists of a metallised ceramic vacuum tube, a set of conductors and a ferrite surround, and is driven by a power amplifier. The components work well within their performance limits and can be tested independently.

We should finally note that the driver amplifier is not saturated and can be used continuously. The deflection system thus lends itself well to a variety of other applications, such as artificial beam blow up, measurement of skew coupling, and the measurement of \( Q \) by determining the phase response of a loop closed by beam. The latter might
allow continuous Q monitoring if beam blow up is not significant.

**Conclusion**

The slow excitation method uses simple technology working will within the limits of commercial equipment, but would require a prototype. The kicker method uses difficult technology but one which is well established at CERN and therefore requires less development effort. The Q-measurement proposal assumes the use of a fast kicker for beam deflection.

### 2.3 Cost of Deflector Systems

The deflector system forms a large portion of the total cost of the Q measuring equipment. However for the fast kicker system we may make use of the driver and magnet units which have been built as prototypes for the extraction kicker.

<table>
<thead>
<tr>
<th>Fast Kicker</th>
<th>Magnet</th>
<th></th>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Ferrite</td>
<td>10</td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mechanics</td>
<td>15</td>
<td>25</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vacuum tank</td>
<td>20</td>
<td>25</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vacuum system</td>
<td>25</td>
<td>25</td>
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<td></td>
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<tr>
<td></td>
<td>Load</td>
<td>15</td>
<td>15</td>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>85</td>
<td>105</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Driver</td>
<td>Capacitor</td>
<td>7.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tank</td>
<td>10.0</td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Thyatron</td>
<td>5.4</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Transformer</td>
<td>4.0</td>
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<tr>
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<td>Power supply</td>
<td>20.0</td>
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<td></td>
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<td>47</td>
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<td></td>
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<td>20</td>
<td>20</td>
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<td></td>
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</tbody>
</table>
3.1. **Pickup Station and Signal Receiver**

The betatron signal will be coupled out using a pickup station provided for beam position monitoring. The station uses 50 ohm matched couplers placed on either side of the beam, and the beam position is determined by comparing the 200 MHz signals in a differential receiver.

The power available from a pickup channel is approximately for the sum signal

\[ P = \frac{1}{2} I^2 R = \frac{1}{2} R (2 f q)^2 \]

where \( q = \frac{e N l}{2 f R_a} \)

Here \( f \) is the operating frequency, \( q \) is the charge induced on the pickup and \( R \) is the system impedance. For 200 MHz, \( 10^{11} \) ppp, 50 ohms this gives a channel power of 0.2 mWatts.

If signals from channels A and B compared in a hybrid to give outputs S and D, then for an input signal \( V \) with \( 1\% \) modulation

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### Table: Services

<table>
<thead>
<tr>
<th>Services</th>
<th>Electronics</th>
<th>50</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Installation</td>
<td>50</td>
</tr>
<tr>
<td>Model, spares</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>150</td>
<td>150k</td>
</tr>
<tr>
<td></td>
<td>474k</td>
<td></td>
</tr>
</tbody>
</table>

### Table: Slow Exciters

<table>
<thead>
<tr>
<th>Slow Exciters</th>
<th>Ferrite</th>
<th>2 x 20k</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceramic tube</td>
<td>2 x 10k</td>
<td></td>
</tr>
<tr>
<td>Power amplifier</td>
<td>2 x 20k</td>
<td></td>
</tr>
<tr>
<td>Power supply</td>
<td>2 x 10k</td>
<td></td>
</tr>
<tr>
<td>Cables</td>
<td>10k</td>
<td></td>
</tr>
<tr>
<td>Spares, model</td>
<td>30k</td>
<td></td>
</tr>
<tr>
<td>Installation</td>
<td>10k</td>
<td></td>
</tr>
<tr>
<td></td>
<td>170k</td>
<td>170k</td>
</tr>
</tbody>
</table>
A = V\sin W_o t(1+0.0\sin W_m t) \\
B = V\sin W_o t(1-0.0\sin W_m t) \\
S = 2 V\sin W_o t \\
D = 2 V\sin W_o (0.0\sin W_m t)

From these expressions we obtain the following power relations,

\text{sum power at } 10^{11} \text{ pp } = -70 \text{ dBW} \\
\text{power in } 1 \% \text{ modulation } = \frac{1}{2}(0.01)^2 \times \text{lower} = -43 \text{ dB} \\
\text{S/N ratio demanded by counter is } = 14 \text{ dB} \\
\text{max noise power } = -70-43-14\text{dBW} = -127 \text{dBW} = 3 \text{ mV in 50 ohms}

An amplifier with a noise figure of 10 dB and bandwidth 60 kHz contributes -146 dBW of thermal noise, so we see that the receiver should be designed carefully. Noise contributions are also made by r.f. power leakage, radiation, transmission cable pickup, amplifier power supplies and vacuum chamber walls. These noise sources should be eliminated if possible.

3.2. Specification for the Betatron Signal Receiver

A tentative specification is given for the differential receiver to be placed in the ring.

Input - two high frequency signals A and B

Frequency 200 MHz
Variation 1 MHz slowly varying
Signal bandwidth -60 kHz
Input power (\frac{1}{2} \text{ sum}) -30 \text{ dBW (at } 10^{13} \text{ ppp - max) }
\text{-70 dBW (at } 10^{11} \text{ ppp - min) }
Matched 50 ohms nominal

Output - one signal D supplied balanced differential

Signal bandwidth 60 kHz
Signal level, max \pm 10 volts between lines
Impedance 110 ohms - POD
Max noise level -137 dBW - referred to input.
4.1. Frequency Measurement by Timing a Number of Zero Transits

The proposed scheme for counting several cycles of the betatron oscillation is illustrated in Fig. 1. The signal in the ring is amplified to a 5 volt working level using a switched gain amplifier. The signal is put through special filters to select the desired frequency band and to reject the strong revolution frequency component.

The sinusoidal signal is then fed to a comparator which delivers a standard TTL pulse for each zero transit. A preset number $N_1$ of these are timed by means of 25 MHz clock. The clock count $N_2$ is then a measure of the betatron period and can be displayed locally or passed to the computer.

The timing of the system is controlled by a real-time clock which is reset at the beginning of each machine cycle. The beam excitation is initiated at preset times $N_0$ and after a delay of about 100 usec the betatron cycle counter and timer are started.

The $Q$-value is obtained in the computer from the expression $N_1 f_2 / N_2 f_r$ where $f_2$ is 25 MHz and $f_r$ is within $\frac{1}{2}$% of 44 kHz and is estimated from the time $N_0$ in the machine cycle.

The accuracy of this method depends on the number of betatron cycles timed and the precision of the zero transit estimation. Landau damping limits the coherence time of the betatron signal to about $1/\Delta Q$ revolutions. For $\Delta Q = \text{less than } 0.01$ we may perform the measurement over 30 revolutions.

The betatron phase change over 30 revolutions is $(Q-n) \times 30.360^\circ$, so that for a precision of $\pm 0.001$ in $Q$, the zero transit must be accurate to $\pm 0.001 \times 30.360 = \pm 12^\circ$. This requires the betatron signal to have a signal to noise ratio after the filter of better than 14 dB.
4.2. Specification for the Counter

Operational limits: for use when the betatron signal envelope has not decayed to less than 25% of starting value (1.86) in 30 revolutions.

Input signal after filter:

- Bandwidth: 22-66 kHz
- Voltage level: 5 Volts peak
- Impedance: 50 ohms nominal
- S/N: 14 dB
- Component at \( f_r \): 30 dB down on signal

Values preset manually or by computer: betatron count \( N_1 \) (one word) and measurement times \( N_0 \) (three words).

Measurement output: Count \( N_3 \) of 25 MHz clock (three words). Accurate to \( \pm 2^\circ \)革命 phase. (i.e. 100 nsec or \( \pm 2 \) bits at 25 MHz).

4.3. Cost of Hardware less Kicker

The counter is designed on a modular basis and uses printed circuit cards that have mostly been designed and are available. Development costs (prototypes etc) are low. Two counter units will be built, and some interwitting will be available to allow one unit to provide a limited service for the other in case of failure.

The cost of one unit is broken down as follows:

- Signal receiver, POD cables: 3.000 SF
- Electronics and control: 5.000 SF
- Power supplies and cables: 2.000 SF
- Two complete units: 20.000 SF
- Two pickups (C.O. Budget): 20.000 SF
4.4. **Frequency Measurement by Computer Analysis**

If the betatron signal decays rapidly the counter technique is not useful, however we may deduce values of $Q$ and $\Delta Q$ from the form of the decay. The measurement process falls into three stages:

| Data Acquisition | Pretreatment & Transformation | Parameter Fitting |

The betatron signal is sampled at say four times the revolution frequency, so that a 256 word buffer is filled after some 60 revolutions which takes about $1\frac{1}{2}$ milliseconds. A diagram of the proposed acquisition hardware is given in Fig. 2.

The data block will then be analysed in the computer to give estimates of the required parameters. The exact algorithm has not yet been decided, as it depends to some extent on the quality of the signal received. It would be based on a 256 point discrete fourier transform using the FFT algorithm.

Some preliminary digital filtering would improve the accuracy when undesirable components can be isolated in the spectra, (e.g. synchrotron modulation), and other preprocessing techniques, such as adding random jitter to remove quantisation components, have also been used with success.

The discrete power spectrum will take the form of a number of bands combed at the sampling rate. To a first approximation the mean and variance of the band give the betatron frequency and its spread. More accurate algorithms for extracting the mean frequency and spread are being studied at the PS.

The data acquisition, FFT, analysis and display may be performed by assembly language routines under the control of the interpretive language by several special commands. An example program using data obtained from the PS, has been written to obtain estimates of execution speed, timing and storage requirements, and so that operating procedures may be evolved.
REFERENCES


2) P. Mills  The Influence of Synchrotron Oscillation on the Betatron Waveform in the SPS. Lab II-CO/Int/BM/PM/72-11


Fig. 1. Q-measurement - Betatron period counter
Fig. 2. Q-measurement - Betatron signal sampling for computer analysis