IEEE Transactions on Nuclear Science, Vol. NS-26, No. 3, June 1979

# ON-LINE Q MEASUREMENT DURING PHASE DISPLACEMENT ACCELERATION IN THE CERN ISR

Douglas Kemp, Ernst Peschardt and Arnold Vaughan*

## Summary

A new technique for measuring Q-values in a coasting beam traversed by RF buckets has been developed based on the RF knock-out principle. At the same time as the bucket traverses the stack a sweeping oscillator excites the beam transversely inside the stack. The resonance created can be detected from a pick-up signal when its radial position coincides with the bucket position. The exciting oscillator is locked to this signal via a phase-locked loop and the Q-value can be measured and stored by a local data acquisition system. At the end of the RF sweep the data is transferred to a computer for further treatment. Automatic control of the working line during phase displacement acceleration is then possible.

## Introduction

The ISR accelerates stacks routinely from 26 to 31 GeV/c by phase displacement[1]. For acceleration of very high intensity beams (up to 36 A) it is essential to have tight control of the Q-values across the aperture (the working line). Local reductions in the chromaticity to values below the threshold for transverse stability can result in total loss of the stack. Experience and transfer function measurements[2] have shown that the stack edges are especially prone to transverse instability. Also, if the working line crosses resonances of order 7 or less, some particle losses will occur when the RF bucket traverses the stack, resulting in unacceptable background conditions for colliding beam experiments.

Operationally, the Q-meter[3] measures the working line across the total aperture using single pulses. With a coasting beam the Q-values at the stack edges can be determined with a transverse Schottky scan but inside the stack only the RF knock-out technique used in the Q-diagram meter[4] can give accurate values of Q as a function of radial position. As originally conceived, this required an RF bucket to traverse the stack for each measured point on the working line, limiting its usefulness for physics stacks. To overcome this limitation a system called the tracking Q-diagram meter has been devised[5]. This instrument uses the empty RF bucket needed for phase displacement acceleration and measures several points inside the stack during one RF sweep.

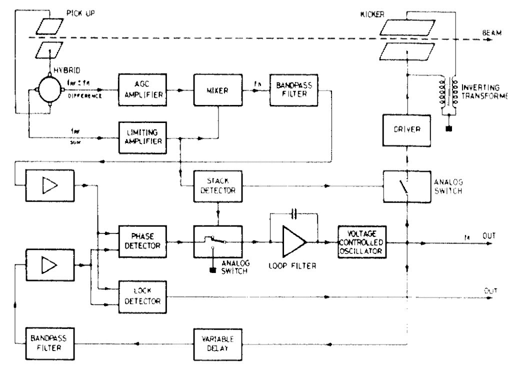
## Principle of operation

The system is based on the technique of RF knock-out to create an artificial resonance in the stack. If a coasting beam is excited transversely with a frequency

$$f_\beta = (n \pm Q)f_{rev}, \; n = \pm 1, 2, 3 \ldots$$

where $f_{rev}$ is the revolution frequency (317.8 kHz at 26 GeV in the ISR) and Q is a tune value inside the stack, the slice of the beam with the Q-value Q will respond causing a coherent transverse oscillation. If, at the same time, an RF bucket passes the excited slice of protons a pick-up will show a modulated bucket signal from which the radial position and the betatron frequency $f_\beta$ can be derived. The demodulated signal with the frequency $f_\beta$ is applied to a phase detector and the perturbing oscillator is locked to a signal recovered from the resonance so excited.

With fast counters for the measurement of excitation and bucket frequency up to 128 Q-values and radial positions can be measured during one phase displacement acceleration sweep which lasts for about 2 s.




BLOCK DIAGRAM OF THE ANALOG PART OF THE TRACKING Q DIAGRAM METER

Fig. 1 Block diagram of the analogue part

## Circuit description

Fig. 1 shows the implementation of the analogue part of the instrument. The input is taken from two opposing electrostatic pick-ups. The sum signal gives the bucket frequency $f_{RF}$ and the difference signal $f_{RF} \pm f_\beta$. These signals are amplified, mixed together and filtered to extract $f_\beta$ which is used as the reference frequency for the phase-locked loop. The output of the voltage controlled oscillator is fed to the beam via the transverse feedback amplifier and kicker[6]. The stack detector, which is triggered when the signal levels are sufficiently high for the proper operation of the system, switches on the excitation and initiates the measurements (Fig. 2). The starting frequency of the voltage controlled oscillator is well above the maximum betatron frequency of the standard working line for high luminosity physics. When the stack detector is triggered the excitation frequency decreases linearly, due to the integrating loop filter, at a rate of about 2 MHz/s. When this frequency coincides with the betatron oscillation frequency ($n = -8$, 159 kHz $< f_\beta <$ 318 kHz) at the bucket position, the oscillator locks and tracks the betatron frequency at the radial position of the RF empty bucket which is sweeping through the stack. The lock detector senses a stable phase condition between the inputs of the phase comparator to indicate when the measurements are valid. The delay and filter in the feedback channel for the phase detector are included to equalise the cable and filter delays in the reference channel.

The local data acquisition system (fig. 3) stores all the necessary information for the measurement of a complete working line. With the time interval selector the time interval between measured points is selected as a function of the RF bucket sweep rate. It triggers

*CERN, Geneva, Switzerland


0018-9499/79/0600-3352$00.75 © 1979 IEEE

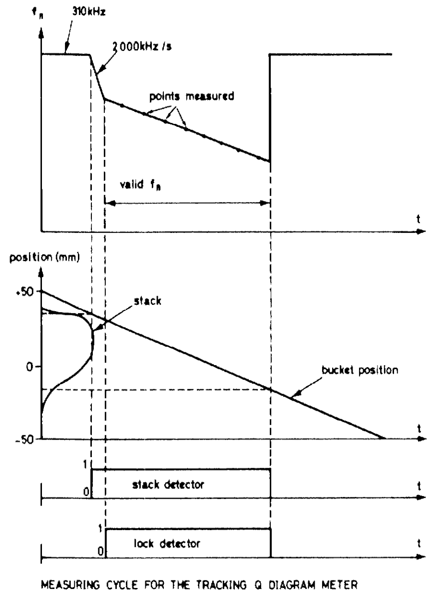



Fig. 2 A typical measuring cycle

the counter for the measurement of $f_\beta$ and the bucket frequency. Simultaneously for a measurement of the beam profile, an analogue to digital converter whose input is the amplitude of the empty bucket signal from a pick-up station, is triggered. For each measured point there are 8 bytes of data which are stored in the local memory. This memory has a capacity for 128 such points.

The interface to the computer is a single width, general-purpose CAMAC module which allows handshake data transfer in both directions and an interrupt (LAM) to signal the end of the RF sweep. A computer program initialises the apparatus, selects the plane and ring for the measurement, takes the new data, converts, checks and normalises it, then generates files of density versus radial position and Q-value versus radial position. These files can be processed by the existing program suites for the longitudinal Schottky scan (density versus radial position) and working line.

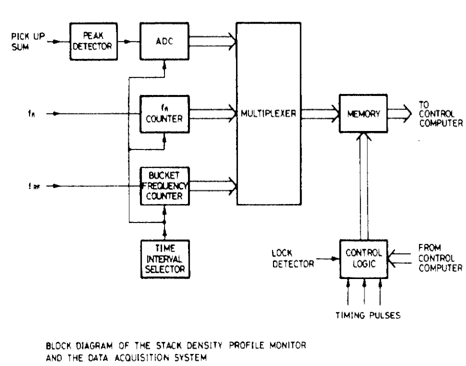



Fig. 3 The local data acquisition system and the density profile monitor

## The performance

### 1. The phase-locked loop

The tracking Q-diagram meter is based on a phase-locked loop whose performance is therefore of great importance. As the betatron frequency varies almost linearly with radial position, the reference frequency for the phase-locked loop is a frequency ramp (phase acceleration). To acquire lock it is known that the loop filter must be of the integrating type which, according to the final value theorem associated with Laplace, gives a constant phase error :

$$\theta_e = \frac{2 \cdot C_a \cdot \tau}{k} \text{ rad/s}$$

where $C_a$ is the rate of frequency change, k the loop gain and $\tau$ the time constant of the loop filter. This phase error introduces a small error in the measured frequency. Other important parameters for the system are the acquisition time for the loop which determines how far into the stack the bucket is when the first measurement is taken and the noise bandwidth of the loop which defines the perturbation of the beam necessary to have a small probability of the loop losing lock. From these contradictory requirements, an acquisition time of 2 ms was chosen giving a loop filter time constant of 4.7 ms and a loop gain of $9.6.10^4$.

With these values the first point of the working line will be measured at a radial position within 3 mm after the stack detector is triggered and the steady state phase error will give an insignificant error in the measured Q-values.

### 2. The precision of the system

The tracking Q-diagram meter measures the non-integral part of the betatron frequency with an accuracy of $\pm 1 \cdot 10^{-4}$. The bucket frequency is measured with a precision of $\pm$ 5 Hz. However, for the calculation of the radial position the momentum must be known as well. For standard RF parameters during phase displacement acceleration at 26 GeV (cavity voltage = 10 kV, $\Gamma$ = 0.2) the gain in momentum of the coasting beam during the traversal of the bucket causes a displacement of the stack of about 1.7 mm which is corrected by increasing the main field. During normal operation the change of the main field is started an undefined time after the RF sweep. The radial position is calculated from the momentum after the RF sweep and the main field increase. Therefore an error of 1.7 mm is introduced at the stack top and an error of 0 to 1.7 mm at the stack bottom.

Another error is introduced by the non-simultaneous measurement of the betatron frequency and the RF bucket frequency. The two measurements are initiated simultaneously but the bucket frequency measurement, which depends on position and momentum, takes between 0.8 and 2.1 ms whilst the betatron frequency measurement, which depends on Q-value, takes 1.6 to 2.5 ms. With the maximum bucket sweep speed, the worst case error is $\pm$ 0.1 mm.

The maximum error is about 2 mm or expressed in Q-value 0.0026 on the ELSA working line.

This gives enough precision to determine how close the beam is to the transverse stability limit and to avoid crossing harmful resonances.

### 3. The effects on the beam

During a working line measurement with the tracking Q-diagram meter the beam is perturbed by a varying frequency which produces a small coherent oscillation moving across the stack.

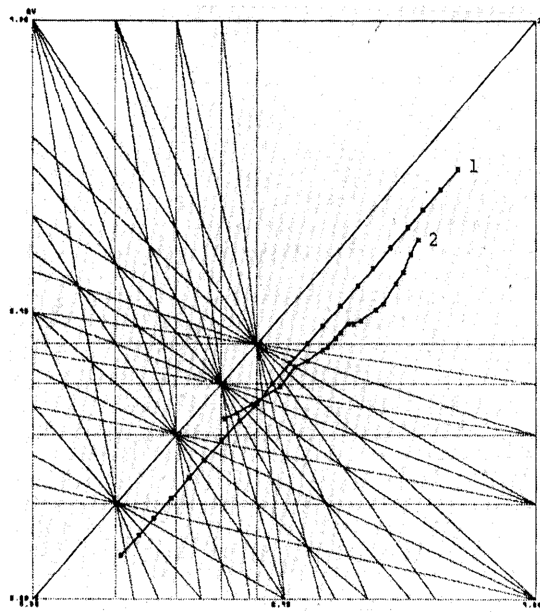



Fig. 4 A $Q_H$-$Q_V$ diagram measured with the tracking Q-diagram meter. 1 : theoretical line, 2 : measured line

In the horizontal plane the emittance blow-up caused by this oscillation is scarcely harmful but in the vertical plane the increase in emittance causes an increase in beam height and hence a reduction in luminosity.

The influence on the effective beam height can be calculated from the formulae[8]

$$\frac{h_n}{h_o} = \sqrt{1 + \tfrac{1}{2}\,\frac{d_t^{\,2}}{h_o^{\,2}}}$$

where $\frac{h_n}{h_o}$ is the ratio of the effective height before and after one sweep, $h_o$ is the initial effective height. $d_t$ is given by

$$d_t = 1.7\,\frac{\sqrt{\beta_{vk} \cdot \beta_{vi} \cdot U}}{\sqrt{f'}} \cdot f_{rev} \cdot 10^{-5}\ \mathrm{mm}$$

where typically f' is the rate of frequency change = 13 kHz/s, $\beta_{vk}$ is the betatron amplitude at the kicker = 50 m, $\beta_{vi}$ is the betatron amplitude in the intersection = 14 m, $f_{rev}$ is the revolution frequency = 318 kHz and U is the applied peak voltage to the kicker = 2 V.

With these values and using an initial effective height of 4 mm one obtains at 26 GeV :

$$\frac{h_n}{h_o} = 1.0004$$

which shows that the perturbation is negligible and 25 working line measurements are possible for a 1% blow-up.

## Experimental Results

The tracking Q-diagram meter gives both the $Q_H$-$Q_V$ diagram as shown in Fig. 4 and the stack density profile as shown in Fig. 5. Repeated measurements show good reproducibility and a comparison with the Q-values obtained from transverse Schottky scans shows good absolute accuracy. An attempt to measure the beam blow-up caused by the system gave no detectable change in effective height after 78 measurements. Operational experience confirms this.

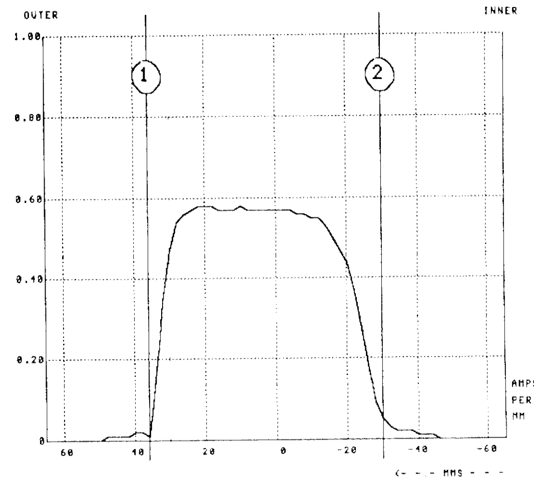



Fig. 5 A density profile measured with the density profile monitor

By deliberately passing an RF bucket across the aperture in both directions the instrument can measure working lines in a stack without accelerating the beam. In this mode of operation the RF cavity voltage is decreased to about 3 kV to minimize the disturbance to the beam. The resulting reduced sweep speed and bucket area increase the accuracy of the system making possible working line measurements with a precision of 0.0015.

## Acknowledgement

The circuitry for the density profile monitor was built by C. Paillard and the front-end electronics for the pick-up by D. Cocq.

## References

[1] E. Ciapala, S. Myers, C. Wyss, Phase Displacement Acceleration of High Intensity Stacks in the CERN ISR, IEEE Trans. Nuclear Science, Vol. NS-24, 3, pp. 1431-1433, 1977.

[2] J. Borer, A. Hoffman, E. Peschardt, Information from Beam Response to Longitudinal and Transverse Excitation, this conference (D-32) (1979).

[3] P. Brown, A direct reading automatic Q-meter for the ISR, CERN-ISR-RF/74-63, 1974.

[4] B. Autin et al, Measurement and compensation of space charge induced Q-shifts in the CERN Intersecting Storage Rings (ISR), IEEE Trans. Nuclear Science, Vol. NS-20, 3, pp. 802-804, 1973.

[5] L. Thorndahl, Private Communication

[6] L. Thorndahl and A. Vaughan, Transverse Feedback for the ISR, IEEE Trans. Nuclear Science, Vol. NS-20, 3, pp. 807-808, 1977.

[7] J. Klapper, S.T. Frankle, Phase-locked and Frequency Feedback Systems, New York, Academic Press, pp. 76-94, 1972.

[8] S. Myers, L. Thorndahl, A. Vaughan, Q-diagram Measurements of Working Lines in Stacks - its Effect on the Stacks, Private Communication, 1974.