STUDY OF BEAM ENVELOPE OSCILLATIONS BY MEASURING THE BEAM TRANSFER FUNCTION WITH QUADRUPOLAR PICK-UP AND KICKER

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ABSTRACT

A quadrupolar pick-up provides information on beam envelope oscillations. To enhance the signals we have used a quadrupolar kicker to excite these modes. In this way the incoherent Laslett tune shift can be directly measured. The tune shifts and spreads of a dense proton beam obtained at LEAR with electron cooling have been studied varying parameters like the number of particles and the cooling time constant. The effects of stop-band on beam distribution as well as on instabilities have been studied. The technique and the results of these measurements will be discussed.

1 INTRODUCTION

The LEAR machine at CERN is currently using an electron cooling device to increase the phase-space density of the antiproton beams at low energy [1]. It is foreseen in the future to use LEAR as an ion accumulator for LHC [2]. Some phenomena like intra-beam scattering (IBS), resonance excitation or instabilities have an influence on the beam quality obtained by electron cooling. To study the behaviour of dense beams, we have installed an ensemble of horizontal and vertical beam profile monitor (BIPM) [3] and a system of quadrupolar pick-up and kicker. The former permits the measurement of the beam profiles and dimensions. The latter permits the evaluation of the tune shifts and spreads [4]. A particular interest has been taken in the influence of the quadrupolar resonance on the beam shape to validate the simulation made by S. Mashida [5]. It is also of great interest to understand better the possibility to screen first-order resonances (normal or skew) by the cooling forces due to the electron cooling.

2 MEASUREMENT OF THE INCOHERENT TUNE SHIFTS

W. Hardt [4] has derived the oscillation frequencies obtained in the presence of space charge forces and gradients errors for elliptical beams (for round beams, they were derived earlier by L. Smith [7]). The incoherent tune shift is related to the measured quadrupolar frequencies by the following relation:

$$Q_{2,x} = 2Q_{0,x} - \left(1.5 - 0.5\frac{a_x}{a_x + a_y}\right)\Delta Q_{inc,x},$$

where the indexes x,y are for horizontal and vertical planes, $Q_{2,x}$ is the quadrupolar frequency, $Q_{0,x}$ is the betatron frequency in the absence of space charge, $\Delta Q_{inc,x}$ is the incoherent tune shift and ax,ay is the horizontal and vertical beam dimensions. A similar expression is obtained for the vertical quadrupolar frequencies exchanging x and y indexes. This result has been obtained for tune shift much smaller than $Q_{0,x}$ and for a homogeneous particle density. For different particle distributions these computations are still valid for the tune shift (taken as the tune offset for particle having zero-amplitude). One can derive more complicated formulae to find the relation between the incoherent tune of individual particles and the measured quadrupolar frequencies. Nevertheless, in first approximation, the distribution in quadrupolar frequencies reflects the amplitude-dependant tune of the beam. As the measurements are taken at low frequencies, the momentum-dependant tune frequency spread is very small with the electron cooling (of the order of 200 Hz while the amplitude-dependant tune frequency spread is larger than 1 kHz).

A quadrupolar pick-up sensitive to the quadrupolar beam shape oscillations [6] is made of four electrodes. The signals of the two horizontal electrodes are summed (as well for the vertical electrodes) for the suppression of the transverse dipole modes. The two signals obtained are then subtracted to suppress the longitudinal mode (sum signal). To enhance the signal, an excitation of the beam envelope is sent through a quadrupolar kicker. A network analyser is used to discriminate the frequency of oscillations. If the beam has a uniform space density, large amplitude quadrupolar oscillations are seen at frequencies close to $(n \pm 2q_{0x,y})f_{rev}$ where $q_{0x,y}$ are the horizontal and vertical non-integer parts of the tunes, f_{rev} is the revolution frequency of the particles and n an integer. As the beam is never perfectly centred neither in the pick-up nor in the kicker, some other frequency lines appear at the dipole and longitudinal mode frequencies. It is also recommended not to look at even mode n as they can be generated by the second harmonics of the dipole modes through non-linearity effects.

At LEAR, the quadrupolar Beam Transfer Function (Q-BTF) was used in conjonction with Beam Ionisation Profile Monitors (BIPM H and V). Figure 1 shows a typical Q-BTF on the vertical plane.

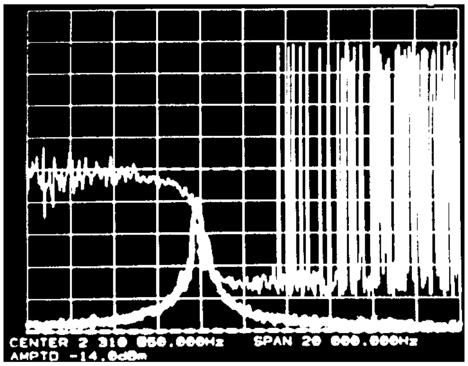

Fig. 1: Typical amplitude and phase of the Q-BTF in the vertical plane at $(3\text{-}2q_v)f_{rev}$. f_{rev} = 1.197 MHz, q_v = 0.577, $\Delta q_{v,inc}$ = -0.06.

We have measured the incoherent tune shift for different electron currents of the electron cooling and for different numbers of particles Fig. 2). The electron cooling and intra-beam scattering forces give a beam dimension equilibrium depending on the number of particles, the electron current and the machine lattices. These relations has been computed for LEAR [8]:

$$\Delta q_{v,inc} = -6.06\left(I_e N\right)^{0.59},$$

where I_e [A] is the electron current and N [10^9] is the number of circulating particles. The incoherent tune shift follows the relation computed above. The vertical coherent tune (Q_v = 2.62) has been moved upwards during the measurements to avoid the effect of the resonance line $2Q_v$ = 5 during the measurements.

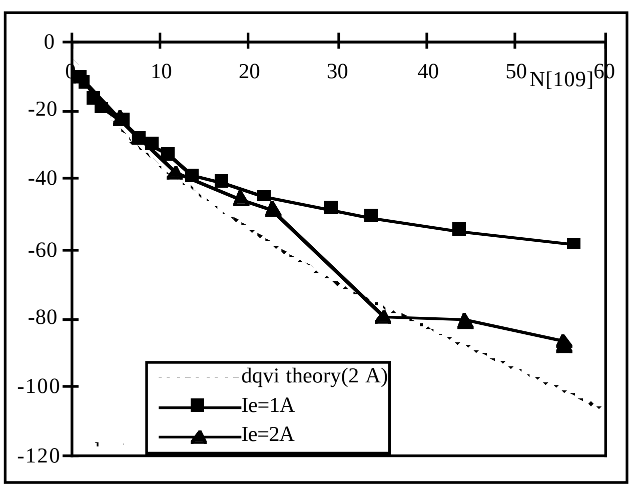

Fig. 2: Measurement of the incoherent tune shift versus the number of protons circulating at 310 MeV/c at LEAR for two values of the electron current of the electron cooling.

3 RESONANCE EFFECTS ON TUNE SHIFT AND BEAM DISTRIBUTIONS

S. Mashida [5] has shown, using particle tracking with space charge, the influence of a half-integer resonance on the beam distribution and the tune shift. The initial gaussian beam distribution in phase space is modified by the presence of the resonance and tends towards a homogeous distribution. The tune shift is limited by the presence of the resonance and the tune spread becomes very small. Above a critical tune there is no significant growth of the emittance.

At LEAR, it is of particular importance to know the influence of the resonances. The consequences on the maximum acceptable width of the resonance or on the chosen working point for the lead ions has to be known. The difference between the presented results obtained with protons and the lead ion operation is the cooling time constant which is about a factor of 50 better (about 50 ms for lead ions instead of a few seconds for protons) [10]. In that case the screening of the resonance by the cooling forces can be better.

A first set of measurements has been taken with $3{\times}10^{10}$ protons at 310 MeV/c under electron cooling to test the half-integer resonance $2Q_v$ = 5. The vertical coherent tune was moved from 2.612 to 2.517 while the horizontal tune was kept constant (Q_h = 2.316). For each point, the coherent tunes, the incoherent tune shifts, the beam projections as seen on the BIPM's have been recorded (Figs. 3, 4 ,5). When the vertical coherent tune is approached to the resonance the vertical beam dimension increases due to the proximity of the incoherent tune to the resonance. The horizontal beam dimension decreases. The intra-beam scattering is less effective due to the large vertical beam size forced by the resonance. Then the cooling forces are leading to a

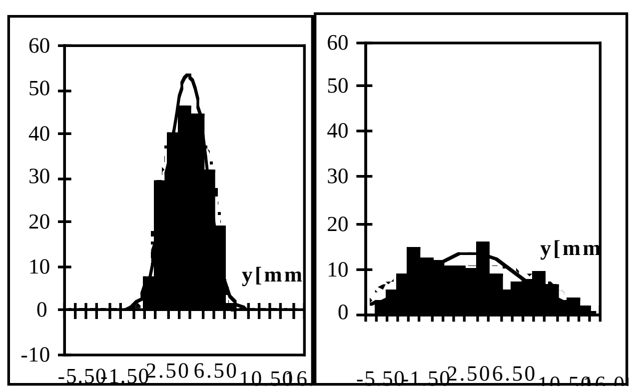

Fig. 3: Vertical beam profiles for coherent tune Q_v = 2.591 (left) and Q_v = 2.523 (right). The homogeneous distribution in phase space (dot) is a better fitting of the profiles than the gaussian distribution (line).

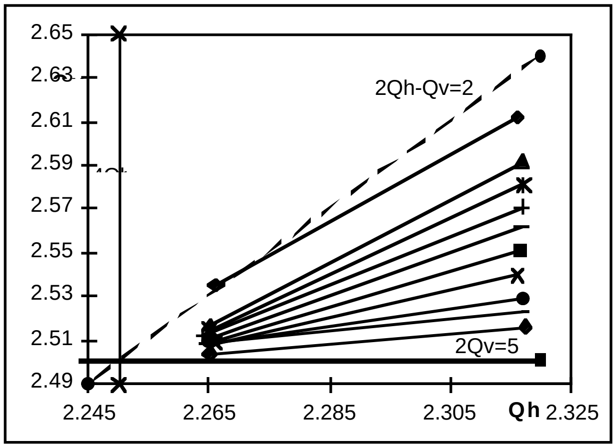

Fig. 4: Measurements of the horizontal and vertical incoherent tune shift while moving the vertical coherent tune closer to the resonance $2Q_v = 5$. The right point represents the coherent tune and the left one is the incoherent tune for the zero-amplitude particle.

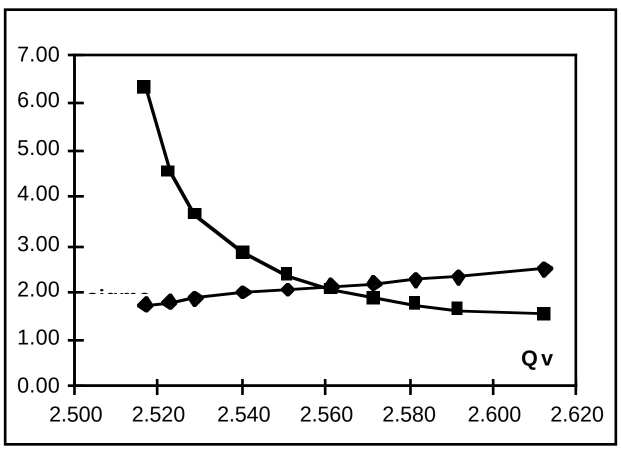

Fig. 5: Evolution of the RMS dimension of the beam while the vertical coherent tune is approached to the resonance $2Q_v = 5$.

smaller horizontal beam size and momentum spread. The vertical beam distribution, as seen on the BIPMV or deduced from the measurement of the frequency spread of the quadrupole mode, indicates a distribution which becomes uniform in phase space but the tune shift computed [9] from the beam size does not support this assumption. From these measurements, a resonance width of 0.008 is deduced. Already with a working point $Q_v = 2.540$, large coherent signals were oberved at different frequencies but it was not possible to distinguish their corresponding modes. It was not possible to move the vertical tune (coherent or incoherent) from above to below the resonance. The resonance should then be compensated. As only skew quadrupoles are available in LEAR, we have tested the resonance $Q_h + Q_v = 5$. When approaching this resonance the same phenomena appeared as above but in the two planes at the same time. After a rough compensation of this resonance it was possible to have the coherent tune above the resonance and the incoherent tune below but not possible to move the coherent tune through the resonance. We conclude that linear resonances should be compensated to a reasonable extent when using electron cooling, to not destroy the good beam characteristics which can be obtained by this method, or machine tunes have to be separated from these resonances.

4 CONCLUSIONS

The quadrupolar beam transfer function is a powerful tool to measuretune shifts and spreads. Together with Beam Ionization Profile Monitors, it permits to analyze the effect of linear resonances.

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