Presentation 1

Horizontally separated encounters in the middle of the arcs

By J.M. Jowett

1.1 Introduction

Although the single bunch intensity has not been an important limit in the present pretzel operation of LEP—the intensities available at injection in 1993 were more than could be put into collision—it is nevertheless true that effects of the mid-arc beam-beam encounters constitute the intensity limit for 8 bunches per beam. In this talk, I shall present some of the criteria, limits and observations on the horizontally-separated encounters in the middle of the arcs.

1.2 Mid-arc encounters

Because the 8 bunches are evenly spaced in the present pretzel scheme, the parasitic beam-beam encounters occur exactly in the middle of the arc, at the centre of the horizontally focussing quadrupole QF49. To provide a complete picture of the beam-beam effects at injection, it is necessary to consider also the long-range effects occurring at the IPs where the beams are vertically separated (these were considered in themselves by the previous speaker [1]).

Figure 1.1 shows the calculated parasitic tune-shifts and other parameters relating to the encounters at the IPs and mid-arc points. These are typical values for the injection conditions used routinely in 1993.[1] The theoretical values are similar with and without the polarization wigglers.

As discussed last year [3] and elsewhere [2], various criteria can be adduced to estimate the severity of the beam-beam effects. The tune-shift parameters given here, namely the values of ξ_x and ξ_y at the *core* of the beam distribution, are just one of these. The separation expressed in units of the beam size is another. Another still is the size and shape of the tune-spread of the beam distribution in the tune diagram, the so-called "footprint". I do not show the latter here but the values of ξ_x and ξ_y can be taken as an indication of its size, if not its shape. As discussed in [4], horizontally-separated encounters add a new lobe to the tune spread which starts at the unperturbed tune and spreads out mainly in the positive Q_y direction. In combination with the

[1] These parameters are calculated using formulas (22)–(23) of [2], valid for beam-beam encounters with any combination of horizontal or vertical separation, as implemented in the program WIGWAM. Until recently, the program always assumed evenly spaced bunches. I take this opportunity to advertise a recent upgrade made in view of the interest in various pretzel, bunch train and 9th bunch schemes with unevenly spaced bunches: given the orbit from MAD and the list of bucket numbers occupied by bunches in each beam, WIGWAM will now locate all the bunch encounters and the elements in which they occur, propagate all the Twiss functions to those points and compute the beam sizes and beam-beam parameters at each encounter.

LEP 1993 injection pretzel, V(ZX)=100 kV, Ib=.3mA

	X/mm	Y/mm	betx	bety	Dx	sigx	sigy	xi_x	xi_y	X/sigx	Y/sigx
IP1	0.323	7	29.0	9.3	0.00	0.2624	0.03318	0.00112	-0.0004	1.23	26.68
QF49.R1	19.1	0.00674	114.7	58.4	1.10	1.438	0.08323	-0.0006	0.00031	13.28	0.00
IP2	0.0615	2	2.7	0.2	0.00	0.07989	0.005163	0.00127	-1E-04	0.77	25.03
QF49.R2	18.3	0.00265	139.6	29.1	1.18	1.542	0.05976	-0.0008	0.00017	11.87	0.00
IP3	0.33	7	29.0	9.2	0.00	0.2623	0.03454	0.00112	-0.0004	1.26	26.69
QF49.R3	18.9	0.00671	114.6	58.5	1.07	1.4	0.08445	-0.0006	0.00032	13.50	0.00
IP4	0.0438	2	2.7	0.2	0.00	0.08	0.005132	0.00128	-1E-04	0.55	25.00
QF49.R4	18.3	0.00293	139.5	29.0	1.15	1.512	0.05872	-0.0008	0.00017	12.10	0.00
IP5	0.321	7	29.0	9.3	0.00	0.2624	0.03317	0.00112	-0.0004	1.22	26.68
QF49.R5	19.1	0.00598	114.5	58.5	1.09	1.419	0.08325	-0.0006	0.00031	13.46	0.00
IP6	0.0606	2	2.7	0.2	0.00	0.07983	0.00516	0.00127	-0.0001	0.76	25.05
QF49.R6	18.4	0.000775	139.5	29.0	1.11	1.467	0.05967	-0.0008	0.00017	12.54	0.00
IP7	0.33	7	29.1	9.3	0.00	0.2625	0.03443	0.00112	-0.0004	1.26	26.67
QF49.R7	18.9	0.00632	114.5	58.5	1.01	1.335	0.0843	-0.0006	0.00032	14.16	0.00
IP8	0.0447	2	2.7	0.2	0.00	0.07989	0.005147	0.00127	-0.0001	0.56	25.03
QF49.R8	18.3	0.00185	139.3	29.0	1.09	1.443	0.05871	-0.0008	0.00017	12.68	0.00

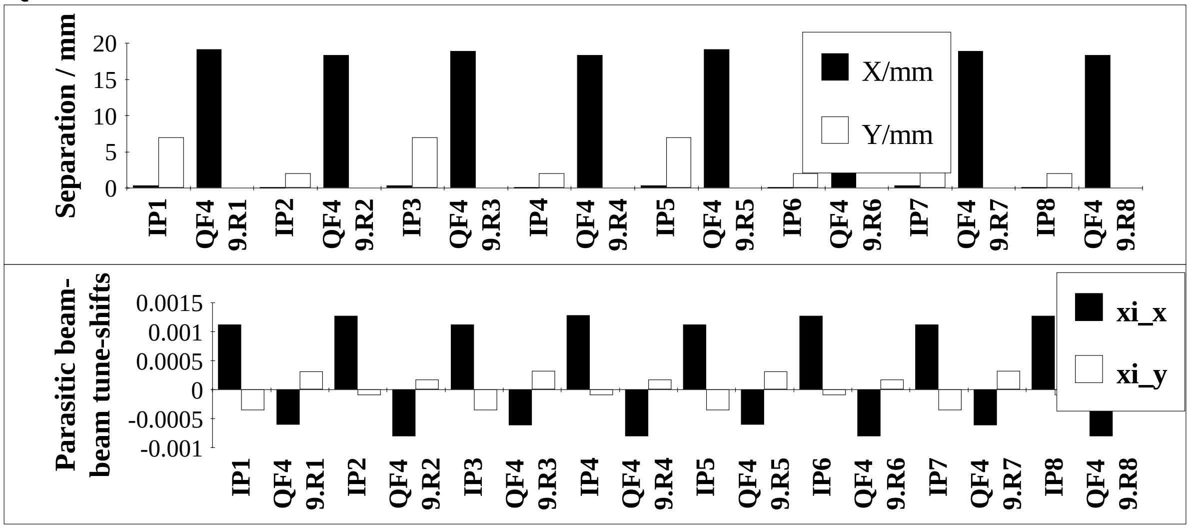

Figure 1.1: Calculated parameters of *all the beam-beam encounters* (i.e., including even and odd interaction points as well as the mid-arcs) for the standard 20 GeV injection conditions of 1993. The machine is assumed to be ideal and a voltage of 100 kV is applied across a gap of 12 cm in each of the 8 pretzel separators (ZX). The current in each bunch is $I_b = 300\,\mu$A and the damping wigglers are on. The orbit and Twiss functions include the local vertical separation bumps created by the ZL separators at the even and odd IPs as well as the long-range pretzel bumps. Their values are computed at the ends of elements by MAD and propagated to the actual locations of the beam-beam encounters by the program WIGWAM which then goes on to compute the beam sizes and beam-beam tune-shift parameters are at each encounter. The last two columns of the table give the horizontal and vertical separations, *both* expressed in units of the horizontal beam size.

tune-spread from head-on collisions, for example, it does not increase the overall spread of either horizontal or vertical tunes very much (in the sense that an upright rectangle circumscribing the footprint does not increase much in size).

Note that the horizontal tune-shifts exceed the vertical at all the encounters but by a smaller factor in the case of the mid-arc encounters. A comparison of the magnitudes of the tune-shifts themselves shows that:

$$\sum_{\text{all encounters}} |\xi_x| \simeq 0.015, \qquad \text{(37\% from mid-arc)} \tag{1.1}$$

$$\sum_{\text{all encounters}} |\xi_y| \simeq 0.0038, \qquad \text{(52\% from mid-arc)} \tag{1.2}$$

$$\tag{1.3}$$

The separations expressed in units of the horizontal beam-size are twice as large at the IPs as at the mid-arcs. (However I shall show later that the values of X/σ_x at the mid-arc points are more than adequate.)

1.3 Optical Side-Effects of Pretzels

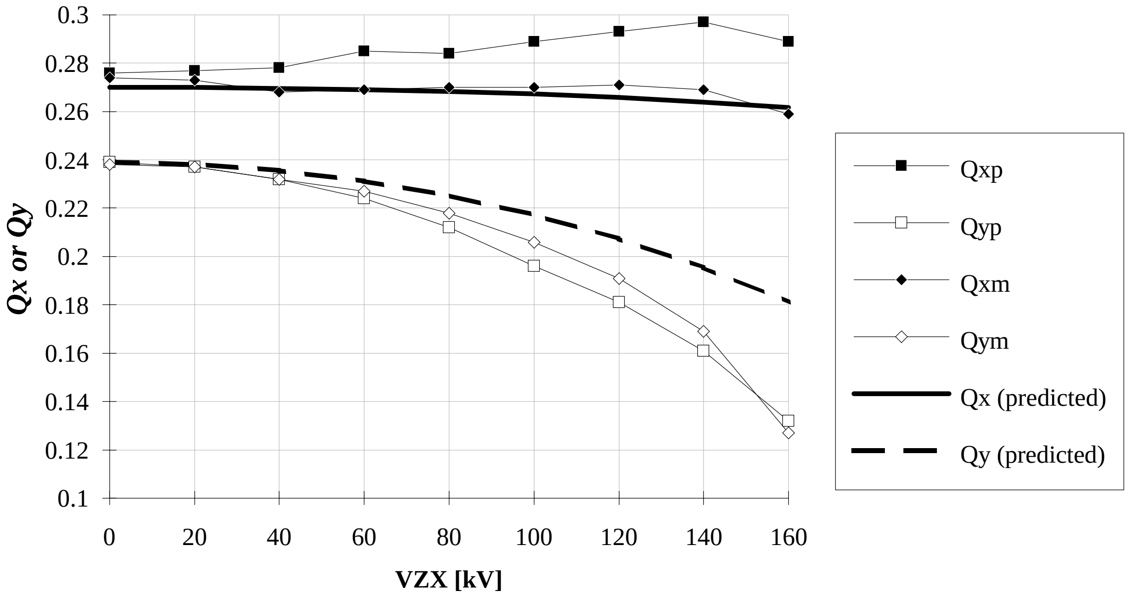

Figure 1.2: Computed and measured tune-shifts with pretzel amplitude at 20 GeV. "Qxp" and "Qxm" denote the measured horizontal tunes for positrons and electrons respectively, etc. The predicted curves were computed with MAD for the ideal G21P20 optics.

Increasing separation reduces the effects of the beam-beam force at the mid-arc points, whatever the nature of the dynamical effects they induce. However the increased pretzel amplitude gives rise to other undesirable effects, mainly connected with the optics and single-particle dynamics, such as tune-shifts and splits, chromaticity shifts and splits and β-beating [5]. Although the pretzel scheme was designed (by building in anti-symmetry of the pretzel orbits about each IP [2]) to make the tune-shifts and chromaticity shifts equal for the two beams, non-zero tune and chromaticity splits do arise in practice because of imperfections in the machine. Figure 1.2 provides a comparison of the change of tune with pretzel amplitude measured (at low intensity) and predicted (by calculation with MAD) for the G21P20 injection optics at 20 GeV.

From these data you can see that tune-splits of the order of 0.02 are typical for the standard settings of the pretzel separators (100 kV at injection).

There are also changes in chromaticity with pretzel amplitude and with intensity (see Section 1.4).

As as by-product of this measurement we can conclude that *aperture is certainly available for larger pretzel separation at 20 GeV*. If the optical perturbations associated with large amplitudes can be dealt with, then this should be the royal road to higher intensities.

Estimates of the chromaticity change from mid-arc beam-beam effects have been calculated and found small with MAD [6]. It is reasonable to conclude that the chromaticity splits are mainly due to optical imperfections resulting in differences between the two pretzel orbits.

1.4 Observations on the Intensity Limit

Here I shall briefly summarise measurements [7] of maximum injected current (carried out in Week 28, 1993) as a function of pretzel separation amplitude. Higher current levels were reached than in a previous experiment (in Week 24), thanks to the availability of longitudinal feedback to deal with longitudinal coupled-bunch instabilities. The currents obtained during the experiment are shown in Figure 1.3. New record single-bunch currents, $I_b > 400\,\mu$A (with 8 bunches in each beam), and total currents, $I^+ + I^- \simeq> 6.4mA$ (in any configuration of bunches), were attained with the help of tune-adjustments, partial equalisation of the e^+e^- chromaticities with the pretzel sextupoles and transverse feedback.

The maximum current attainable is shown as a function of pretzel separation in Figure 1.4. At small separations, the limit appears to be due to well-known incoherent beam-beam effects. It can be seen by scaling from Figure 1.1 that a separator voltage of 50 kV is enough to reduce these to insignificance, both in terms of long-range tune-shifts and separation of beam cores.

The chromaticities must be adjusted as both beams increase in intensity. The limit in current occurred when the horizontal chromaticity Q'_x vanished for one beam and was too high for the other, i.e., there was effectively a chromaticity split (of about 1.5 units). There was partial success in equalising the chromaticities with the pretzel sextupoles.

The chromaticity settings which stabilised the beam at $I_b \simeq 400\,\mu$A were found to be too low to inject again with low current. After killing the high intensity beam we could only inject $I_b \simeq 50\,\mu$A and the chromaticity was found to be -1. This behaviour can be explained by a chromatic effect of the beam-beam force in the mid-arc crossings. The sextupole component of the long range beam-beam force, combined with the dispersion in the mid-arc, leads to momentum-dependent beam-beam kicks. In the first approximation this effect has an opposite sign every other crossing so that the effect should cancel out, but systematic errors due to the pretzel could result in a net chromaticity change [7, 6].

The mode spectra at high intensity just before and after the loss of the positron beam (seen on the right of Figure 1.3 are shown in Figure 1.6 and 1.6. These show that the mid-arc beam-beam interaction generates a mode "$m = -1$" at a large fraction of the synchrotron tune $Q_s \simeq 0.07$ below the coherent tune.

Another, currently unexplained, mode appears between the two lines. This appears even without the mid-arc beam-beam interactions and probably shows us that the present theory of head-tail modes and the transverse mode-coupling instability is incomplete.

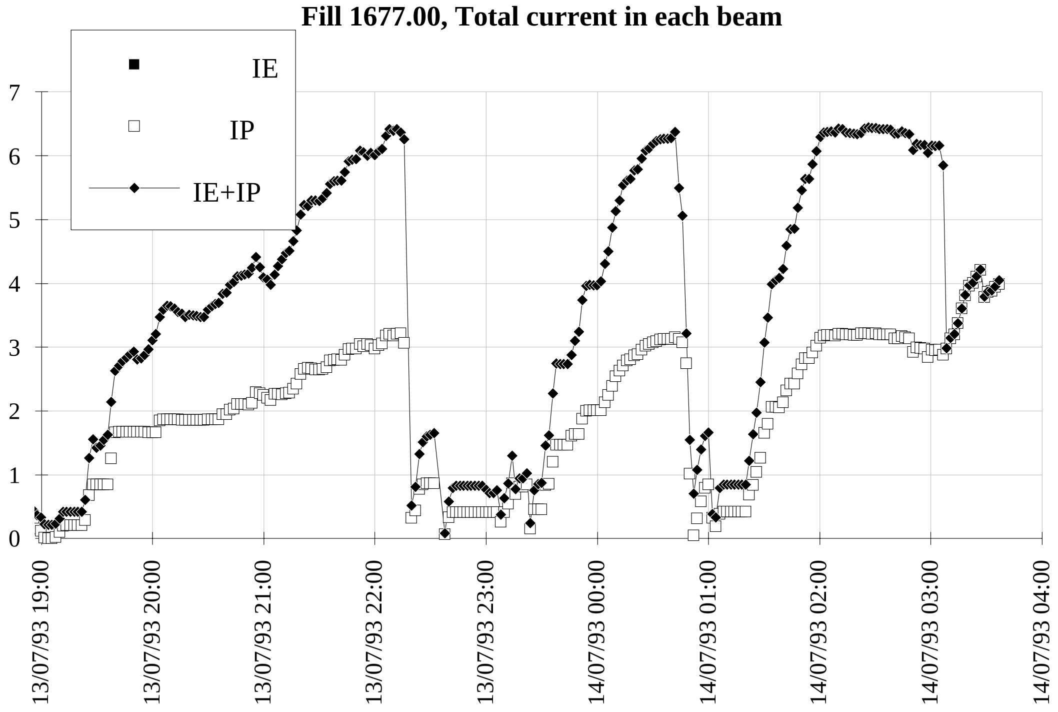

Figure 1.3: Total electron and positron currents in mA during an experiment described in the text. Thanks to the beam-current equaliser, the data points for the electron ("IE") are invisible since they are identical to those for the positrons ("IP"). At the end of the experiment, all the positrons were lost.

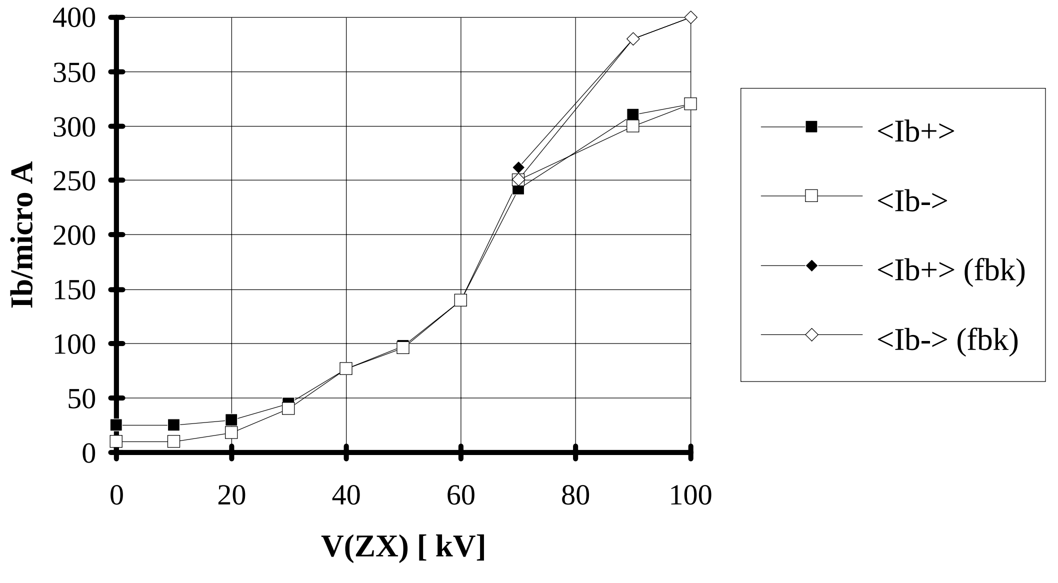

Figure 1.4: Current limit with 8 bunches in each of two beams vs. voltage in the pretzel separators, $V(\mathrm{ZX})$. The higher branch of data for $V(\mathrm{ZX}) > 70\,\mathrm{kV}$ was obtained with the help of the longitudinal feedback system.

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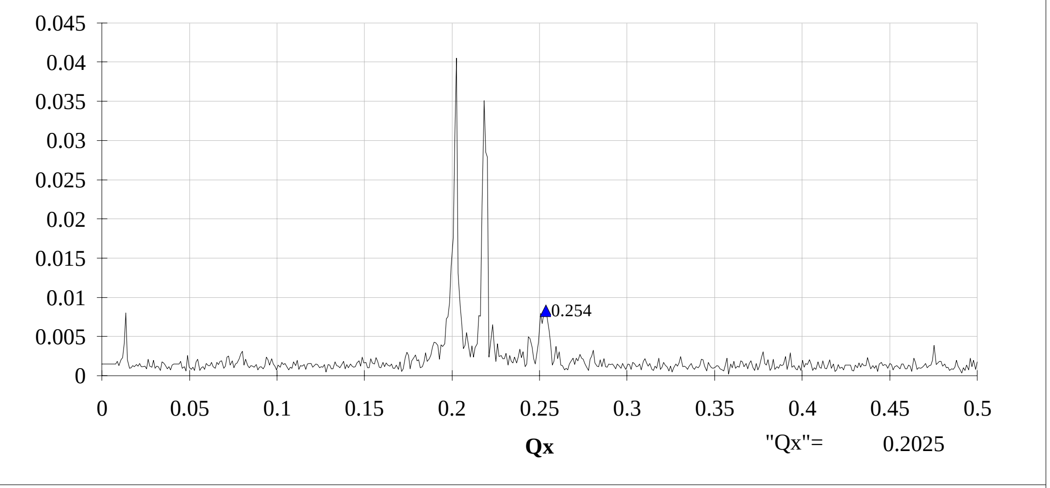
LEP transverse oscillation spectra, saved by Q-meter FFT mode

Two beams of 8 bunches near intensity limit. No transverse feedback.

Origin	%16s	FFT	
Timestamp	%16s	**14:2:7:37**	
Mode	%16s	SEQUENTIAL	
Number_of_bins	%4hd		512
Hor_bunch_excited	%2hd	IE IP	**9**
Hor_bunch_observed	%2hd	3.195 3.189	**5**
Ver_bunch_excited	%2hd		**9**
Ver_bunch_observed	%2hd		**5**
Column	**Qx**	**Qy**	**Ax**
1	0	0	0.001486
2	0.001	0.001	0.001486
3	0.002	0.002	0.001486
4	0.0029	0.0029	0.001486



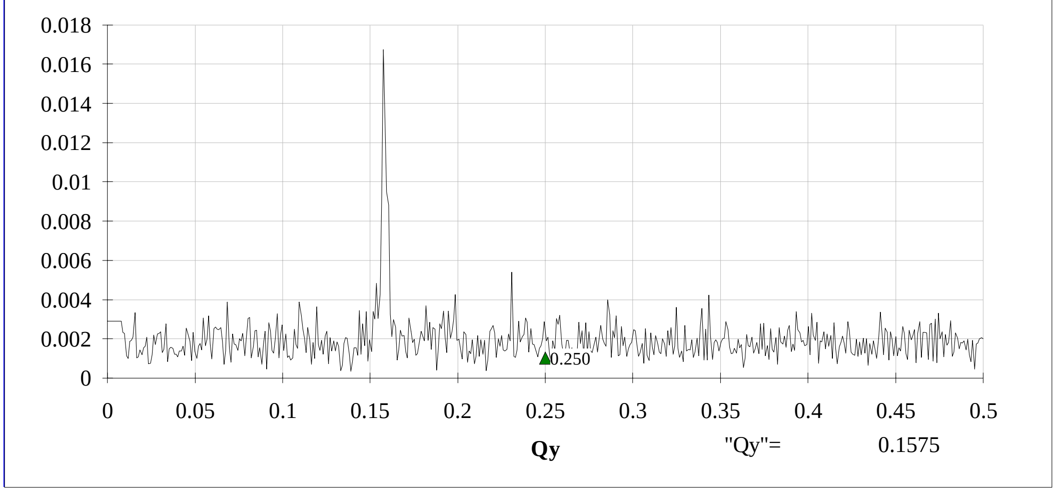


Figure 1.5: Spectra of transverse motion of the beam taken with the Q-meter in FFT mode with *high intensities in both beams*. In the horizontal plane, the "$m = -1$" mode comes up very strongly and is much larger than the coherent tune itself.

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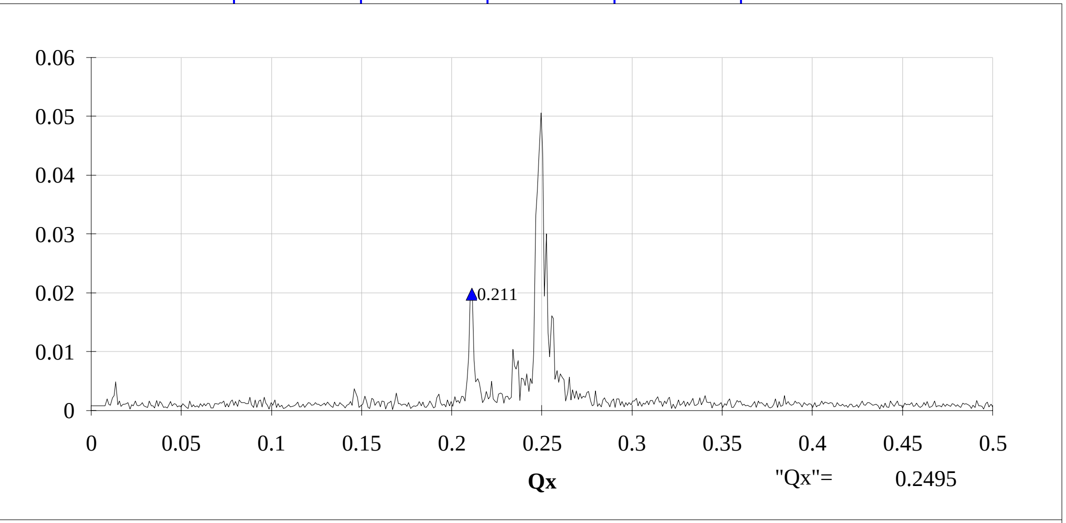
LEP transverse oscillation spectra, saved by Q-meter FFT mode

After loss of electron beam.

Origin	%16s	FFT	
Timestamp	%16s	**14:3:20:12**	
Mode	%16s	SEQUENTIAL	
Number_of_bins	%4hd		512
Hor_bunch_excited	%2hd	IE IP	9
Hor_bunch_observed	%2hd	0.008 3.964	9
Ver_bunch_excited	%2hd		9
Ver_bunch_observed	%2hd		9

Column	**Qx**	**Qy**	**Ax**	
1	0	0	0.00084	
2	0.001	0.001	0.00084	
3	0.002	0.002	0.00084	
4	0.0029	0.0029	0.00084	0.002634



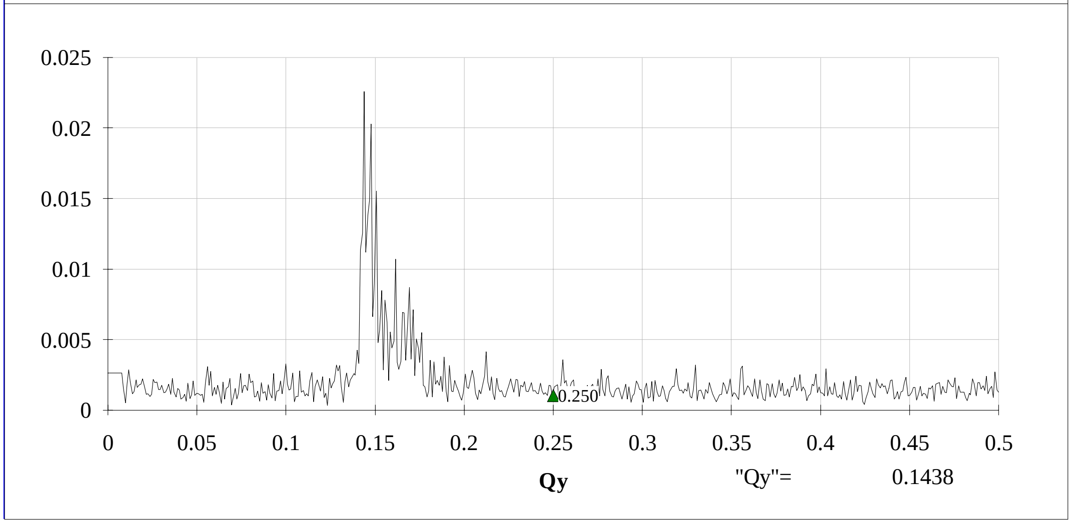


Figure 1.6: Spectra of transverse motion of the beam taken with the Q-meter in FFT mode with *high intensities in one beam only*. The "$m = -1$" mode is now barely visible in the horizontal plane.

Figure 1.7 was prepared by looking at the amplitudes of the "$m = -1$" modes on many spectra like Figure 1.6 taken at different values of the beam current. This confirms that the amplitude of mode grows with current only when there are two beams.

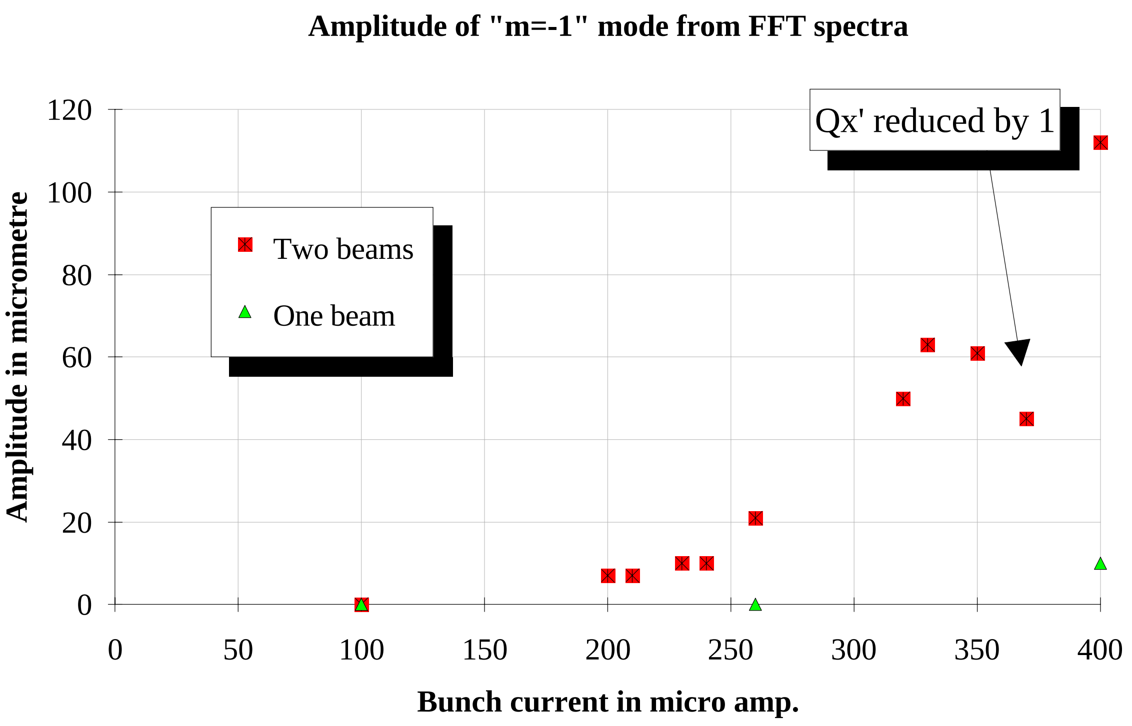


Figure 1.7: Amplitude of "$m = -1$" mode, taken from the Q-meter's FFT spectra, as a function of single bunch current, I_b. Data are shown for two beams in the machine and for a single beam. They show clearly that the mode is much more strongly excited when two beams are present. (Figure from [7], prepared by K. Cornelis.)

In a later measurement (Fill nos. 1683 and 1684), still higher currents ($I_b \simeq 430\,\mu$A in each of the 16 bunches and the (still-standing) record total current for LEP of 6.6 mA) were obtained with the help of the transverse feedback acting as a straightforward damper. The horizontal chromaticity was reduced to zero and a subsequent low intensity measurement gave

$$Q'_x \simeq 0, \qquad Q'_y = 3 \tag{1.4}$$

for both beams. Equality of the chromaticities was this time achieved with the help of empirical trims of the pretzel sextupoles. The extra dispersion generated by the pretzel orbits at these sextupoles was presumably enough for them to act as differential chromaticity trims. If there had been the opportunity to make detailed dispersion measurements as in [5] it might have been possible to predict their effect quantitatively.

Later in the year (Fill no. 1724) similar techniques allowed 4.4 mA to be accumulated in the 8 positron bunches, giving $I_b \simeq 550\,\mu$A. It was then *easy to accumulate* electrons starting from zero intensity, a further confirmation that parasitic beam-beam effects do not limit the intensity with the standard separations. However saturation then occurred at a total electron current of 0.54 mA.

1.5 Coherent beam-beam modes

In [8], the rigid-dipole coherent beam-beam modes were analysed using a model which included the beam-beam interactions in the mid-arc. From this analysis, it can be concluded that, although such phenomena are not to be expected with the usual tunes and parameters of the LEP pretzel scheme (the instabilities could only be made to appear by reducing the pretzel separation in the calculations), there may be some benefit in moving to higher horizontal tune, especially if substantially larger intensities are achieved in future.

1.6 Conclusions

It is now quite clear that the single-bunch intensity limit is due to coherent effects involving the mid-arc beam-beam encounters and a model to explain the mechanism has been proposed [9].

Work on the intensity limit needs to continue in 1994. Since much of the scheduled MD time was lost in 1993, there remain hopes for gains from the use of polarization wigglers, high Q_s and feedback. However the most likely way of increasing the current per bunch will proceed via optical corrections to reduce the tune and chromaticity splits, thereby allowing larger pretzel amplitudes. This work will be fairly time-comsuming and difficult. A realistic goal for 1994 would be to get $I_b \simeq 500\,\mu$A into physics. If parallel work on the physics conditions allows higher currents to be collided then luminosity gains should result. Pretzel operation of LEP2 would certainly also benefit from higher injected currents.

Increased Q_x might help to avoid coherent beam-beam effects (although there is no clear evidence that these play a significant rôle) and, given the form of the beam-beam tune-spread, it may be better to work with tunes above the main diagonal in the tune diagram (i.e. $Q_y > Q_x($ mod 1)). We recall that the very first "pretzel" optics used for pilot MD studies in 1991 [10] had such tunes and no particular problems were encountered with it.

References

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