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Bunch current limit with high Q_s and octupoles

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Summary

Two methods have been tried to increase the current per bunch in preparation for LEP 2. First the installed octupoles were powered at injection to increase the spread in the betatron frequencies in the hope to influence the transverse mode coupling (TMC) instability. The spreads that can be obtained are rather small even when using the emittance wigglers to help the octupoles. With such small values not much effect was expected but the experiment was tried anyway. With a synchrotron tune of $Q_s \approx 0.083$ the maximum current without the octupoles was about 0.54 mA per bunch limited by a vertical TMC instability. Powering the octupoles with -55 A (sign giving larger tune spread) the TMC instability appears at about 0.51 mA and kills often half of the current. Using the octupoles a +55 the threshold is reached at about 0.5 mA/bunch but in a smooth fashion without current loss. Later the octupoles were tried again at a higher Q_s without giving a current increase.

The second experiment used the damping, emittance and polarization wigglers close to their maximum values. With growing synchrotron tune the bunch current increased reaching the maximum values of 0.816 mA in one bunch and 3.18 mA in four bunches for $Q_s \approx 0.126$. Apart from a slight correction of the horizontal chromaticity no other adjustments were necessary.

1 The octupoles

A total of eight octupoles have been installed in LEP last year close to the interaction points. The magnetic length of each is 0.417 m and the strength at 55 A is $d^3B/dr^3 = 1153\ \mathrm{T/m^3}$. The beta functions at these octupoles are $\beta_x \approx 225$ m and $\beta_y \approx 21$ m with the exception of one located on the right of point 2 which has $\beta_x \approx 152$ m. At 20 GeV, the tune changes due to a static horizontal or vertical displacement Δx_0 then are $\Delta Q_x = 493\Delta x_0^2$, $\Delta Q_y = -48\Delta x_0^2$. For a horizontal oscillation of amplitude $\hat{x}$ the above factors are smaller by 1/4 for the horizontal and 1/2 for the vertical tunes [1] which gives $\delta Q_x = 123\hat{x}^2$ and $\delta Q_y = -24\hat{x}^2$. Expressed in the emittance of the oscillation $E_{x0} = \hat{x}^2/\beta_x$, $\delta Q_x = 26800E_{x0}$ and $\delta Q_y = -5200E_{x0}$. For a

[1] We thank J. Gareyte for clarifying this point

E-wiggler	D-wiggler	P-wiggler	E_x	$\delta Q_{x,rms}$	$\delta Q_{y,rms}$
			nm rad		
off	off	off	2.6	0.00025	0.00003
on	on	off	32	0.0024	0.0005
on	on	on	19	0.0014	0.0003

Table 1: Calculated tune spreads and damping rates due to the octupoles for different wiggler configurations

I-octupole	dQ_x/dE_{x0} measured	dQ_x/dE_{x0} expected
A	$\mathrm{m}^{-1}\,\mathrm{rad}^{-1}$	$\mathrm{m}^{-1}\,\mathrm{rad}^{-1}$
0	-80000	≈ 0
+55	110000	26800

Table 2: Measurement of the tune with amplitude using phase lock

beam with a horizontal emittance E_x we find for the rms tune spreads $\delta Q_{x,rms} = 75800 E_x$ and $\delta Q_{y,rms} = 14700 E_x$. The natural emittance without wigglers is very small at 20 GeV and does not lead to a significant tune spread with the octupoles. We can improve this situation with the emittance wigglers. The relevant parameters are listed in table 1 for the different wiggler configurations.

The frequency spreads which can be achieved with the octupoles are rather small specially in the vertical plane where the limitation is more important. However, since the octupoles are available, the experiment was tried anyway.

2 Measurements with the octupoles

As a start we measured the betatron tune spread obtained with the octupoles. In the first experiment we measured the tunes as a function of horizontal betatron amplitudes using the phase lock system. A coherent oscillation with increasing amplitude is excited and the tune change measured. The results are shown in table 2. The sign of the powered octupole was not known beforehand but determined by this experiment. The obtained values seem to be too large. This is not well understood but it could have two causes. The beam emittance could be larger than the theoretical one due to optics errors or to the excitation leading to some incoherent blow up. The phase of the Q-meter could lock to a fix point of the non-linear oscillator represented by the beam in the octupole.

In the second run the tunes and theirs spread were measured as a function of emittance without using a coherent oscillation of large amplitude. This was carried out with the emittance wigglers and the Q-meter operating in the FFT and the swept frequency mode. The results are shown in table 3.

The measured tune spread dependence on horizontal emittance is very small and within the errors consistent with the expected value. The horizontal tune stays constant while the vertical increases with emittance. The latter effect is caused by the vertical focusing of the wigglers.

With the emittance wiggler at its maximum value the octupoles were turned on and the

E-wiggler	E_x calculated	Q_x	$\delta Q_{x,rms}$	Q_y	$\delta Q_{x,rms}$	method
$\int Bdl$ T m	nm rad					
0	2.6	0.2690	0.0012	.2225	.0004	FFT
0.44	5.9	0.2716	0.0014	.2228	.0009	FFT
		0.2741	0.0024	.2284	.0008	swept freq.
0.84	23	0.2718	0.0013	.2278	.0013	FFT
		0.2744	0.0010	.2335	.0007	swept freq.

Table 3: Measurement of tunes and spreads vs. emittance without octupoles

I-octupole	E-wiggler	E_x calculated	Q_x	$\delta Q_{x,rms}$	Q_x	$\delta Q_{x,rms}$	method
A	$\int Bdl$ T m	nm rad					
+55	0.84	23	0.2760	0.0016	.2280	.0010	FFT
			0.2777	0.0012	.2343	.0008	swept freq.
-55	0.84	23	0.2700	0.0021	.2349	.0011	FFT
			0.2685	0.0028	.2294	.0009	swept freq.

Table 4: Tunes and spreads with the octupoles and emittance wigglers

resulting change in tune and spread measured. The results are shown in Table 4.

The increase of the horizontal tune spread due to the octupole is visible while the effect in the vertical plane cannot be resolved. Taking the measured horizontal spreads with the octupoles and using a quadratic subtraction of the values without the octupoles we get for the average of both polarities $\delta Q_{x,rms}/E_x = 85000\,\mathrm{m}^{-1}\mathrm{rad}^{-1}$ which agrees with expectation but has a large error.

Next the octupoles and the emittance wigglers were turned off but the damping wiggler kept on. With a synchrotron tune of Q_s=0.083 a maximum current of about 0.54 mA per bunch was obtained limited by the vertical TMC instability. Using the octupoles at -55 A this threshold was reduced to about 0.51 mA per bunch. At this value a large sudden current loss occurred. Using the octupoles with the opposite polarity at +55 A the beam saturated at about 0.50 mA per bunch without current loss. Later the octupoles were tried at a higher synchrotron tune, again without achieving a current increase.

3 Current limit with all wigglers and high synchrotron tune

The octupoles were turned off and different configurations of wigglers were used. Only the horizontal chromaticity was corrected and no other adjustment was necessary. The increase of the current in one and in four bunches with increasing synchrotron tune was measured. of synchrotron tune. A maximum RF-voltage of about 335 MV including the superconducting cavities was obtained. The results are listed in table 5 and plotted in Fig. 1. Clearly the current per bunch increases with Q_s. The highest currents achieved were 0.816 mA per bunch and 3.18 mA in four bunches. Both are new records and exceed the design values. Although the measurement errors are not very small and other instabilities (e.g. longitudinal effects) might occur at higher bunch current we could not resist the temptation to extrapolate the data to the full RF-voltage which will available in LEP 2 (giving $Q_s \approx 0.3$ at 20 GeV) to

E-wiggler	D-wiggler	P-wiggler	Q_s	σ_s	I per bunch	I in 4 bunches
		f		mm	mA	mA
off	on	off	0.083		0.540	
off	on	off	0.101	13	0.615	
off	on	on	0.101	15	0.728	
off	on	on	0.108		0.742	
off	on	on	0.111	12	0.760	2.9
on	on	on	0.120	≈14	0.794	2.97
on	on	on	0.122		0.809	3.18
on	on	on	0.126		0.816	3.18

Table 5: Current limits for different synchrotron tunes and wiggler configurations

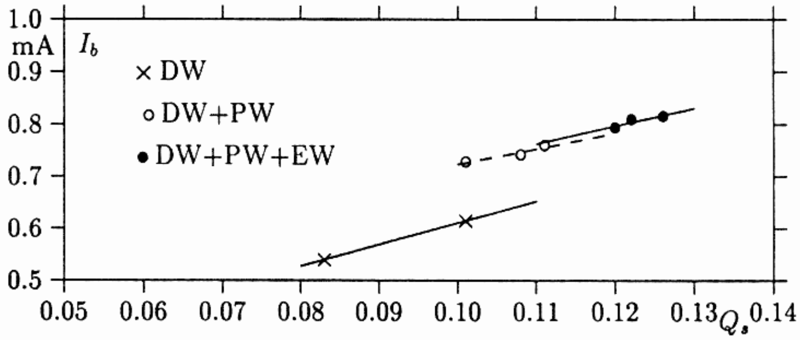

Figure 1: Bunch current for different wiggler configurations and synchrotron tunes

find a maximum expected bunch current of about 1.3 mA.

At the end the RF-frequency was increased by 200 Hz to reduce the longitudinal damping partition. With all the wigglers turned on, the variation of this partition with ΔE small $(dJ_E/(d\Delta E/E) = 120)$ and increase in bunch length was not significant. No increase in beam current could be observed.

4 Conclusions

The frequency spread provided by the available octupoles did not increase the TMC threshold. This is expected based on investigations by G. Besnier Y.H. Chin and A. Chao. Increasing the synchrotron tune and keeping the bunch length as long as possible with all the wigglers, improved the beam stability yielding over 0.8 mA in one and over 3 mA in four bunches. These values are of not much use for the present LEP operation where beam-beam effects would represent a limitation,but are very promising for LEP 2 operation at higher energy. Based on the observed current dependance on Q_s, there is hope that with the higher RF-voltage that will be available, currents in excess of 1 mA per bunch may be achieved. It still has to be shown that the large currents per bunch can also be achieved with two beams and are not limited by long range beam-beam effects at injection.