Injection and Accumulation of High Currents – Performance, Limitations and Expectations for 1999

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Abstract

The performance of the LEP injection and accumulation is reviewed for 1998, including the observations from standard operation and special machine studies. The observed and expected limit in total accumulated beam current at 22 GeV is discussed and the required machine conditions are described. While the beam current determines the LEP2 peak performance, the achievable efficiency and reliability of beam injection and accumulation can limit the integrated luminosity. Possible ways to further improve both efficiency and reliability are discussed.

1 INTRODUCTION

The achievable luminosity in any storage ring is a steep function of the stored beam current. In the regime without beam-beam related beam blow-up the luminosity increases with the square of the beam current. In order to prepare for LEP2 high energy running several measures have been taken in the past years to allow maximum beam energy and maximum beam currents:

- 1994/95: Double batch synchrotron injection [1].
- 1995: Injection into beam optics with intermediate squeeze [2].
- 1995: Injection at 22 GeV instead of 20 GeV [3].
- 1996-1999: Substitution of low gradient and high transverse impedance copper RF units with superconducting RF units.

Those changes helped to both achieve the desired 1 mA limit of bunch current at injection energy and to improve the efficiency of the injection process. The only significant change in injection for 1998 with respect to the end of 1997 had been the removal of 38 copper RF units and the associated reduction in the transverse impedance. High energy running in 1998 was performed exclusively with two beams each consisting of four equidistant bunches. As the same mode of operation is foreseen for 1999 bunch train issues for injection are not discussed in this paper.

2 INJECTION PERFORMANCE IN 1998

The LEP injection and accumulation systems allowed operating LEP in 1998 with the highest ever physics beam currents. The typical beam current was increased by 15 % with respect to 1997. From this improvement alone one expects a 33% increase in luminosity. The injection performance for 1998 is summarized in Table 1 and compared to the 1997 values. In the following sections we discuss the 1998 beam currents at injection, the turn-around and the injection efficiency in more detail.

Table 1: Comparison of typical bunch and total beam currents in 1998 and 1997.

Year	Bunch Current [μA]	Total Current [mA]
1997	650	5.2
1998	750	6.0

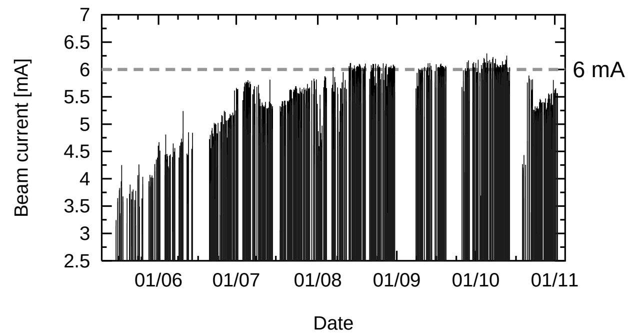

Figure 1: Total accumulated beam current at 22 GeV during the 1998 LEP run.

2.1. *Evolution of Beam Currents*

The maximum accumulated beam currents at injection energy are shown in Figure 1 for the 1998 run. Several regimes can be distinguished:

1. June to August: Slow increase of total beam current from 4 mA to 6 mA. A hardware limitation due to the heating of certain RF cables had been realized [4]. The limit was depending on beam current and bunch length. Modifications in the machine settings during the energy ramp were introduced in order to assure the maximum possible bunch length at all LEP energies [5]. The bunch length that ultimately was achieved imposed a 6 mA limit on the total beam current. This beam current was reached in the first half of August.
2. August to September: The 6 mA current limit from the RF cables was routinely achieved during accumulation. Improvements were implemented in the transmission of beam current up to the 94.5 GeV physics energy.

3. September-October: The intensity limitation was relaxed somewhat and beam currents slightly above 6 mA were filled.
4. Second half of October: At that time 30 melted RF cables were leaving 8 cavities without control. The current limit was lowered to about 5.5 mA in order to avoid serious further damage.

The operational intensity in LEP was at no point in 1998 limited from the injection or accumulation but always from the allowable heating of the RF cables. We conclude that the injection and accumulation systems of LEP supported the excellent LEP performance in 1998 up to maximum intensities.

2.2. Required Time for Injection and Accumulation

As the beam intensity determines the peak luminosity, the time required to fill and accumulate the 6 mA total beam current limits to some extent the integrated luminosity. LEP2 physics fills in 1998 lasted an average time of only 207 min, or about 3.5 hours. As soon as the beams are brought into collision the beam currents are decaying fast, mainly due to particles lost in radiative Bhabha scattering or beam-beam bremsstrahlung. The lifetime at the start of a physics fill in 1998 was usually below 5 hours. In order to optimize the integrated luminosity one would require that injection and accumulation is much faster than the length of a physics fill.

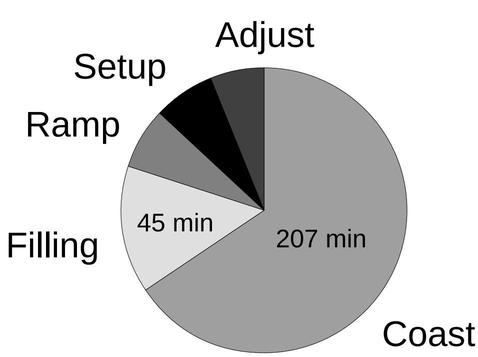

Figure 2 Distribution of time spent in different LEP modes for the average 1998 physics fill with a total length of 315 min.

The average time spent in the different LEP modes is shown in Figure 2. It is seen that the 207 min in physics mode ("Coast") must be compared to 45 min in filling mode. The 45 min are much longer than the time needed in order to obtain the required 6 mA from the SPS. Depending on the cycle, the SPS can deliver the 6 mA beam current in 4-5 min to LEP. It is evident that LEP cannot make use of that beam rate. In order to further examine this problem the distribution of fills with a given "filling time" is shown in Figure 3.

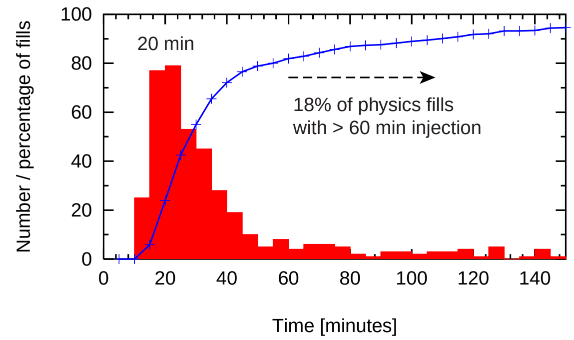

Figure 3: Distribution of the time that 1998 physics fills spent in filling mode (histogram). The curve indicates the percentage of fills that had a "filling time" equal or shorter than the given value.

From Figure 3 we can see that the most probable time to fill LEP is about 20 min. However, about 20 % of the fills remain for an hour or longer in filling mode. Those extraordinary delays in injection have been analyzed [6]:

- ~ 1/3 were caused by injector chain problems.
- ~ 1/3 were caused by equipment faults.
- ~ 1/3 were caused by RF problems.

The equipment groups work on reducing the fault rates, though it must be realized that there is some unavoidable minimum rate of faults.

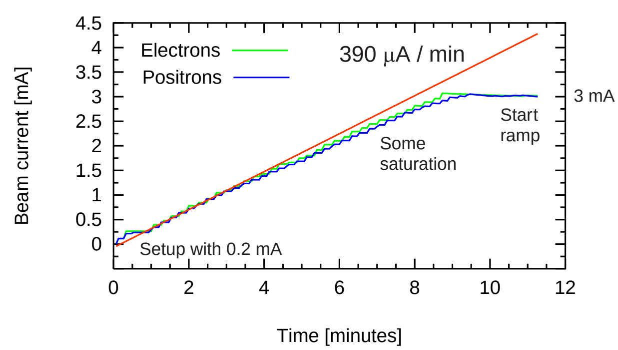

Figure 4: Example of very good filling for physics fill #5045. Note that the single beam current is shown as a function of time. The current limit is here 3 mA.

Considering the 20 min typical fill time it must be noted that it is a factor of ~4 above the time expected from the SPS beam delivery. Figure 4 shows an example of very good filling for physics fill #5045. The target single beam current was reached in ~10 min with an initial fill rate of 390 μA/min. The fill rate was only slightly reduced at higher currents. Electron and positron injections behave very similar. Note the operational overhead of 3-4 min due to the tune setup at low current, the Q-loop preparation at high currents and the preparation and start of the ramp. Figure 5 shows the effective filling rate for all physics fills in 1998. This effective filling rate is defined as the single beam current divided by the time spent in filling mode, after subtraction of a 4 min operational overhead.

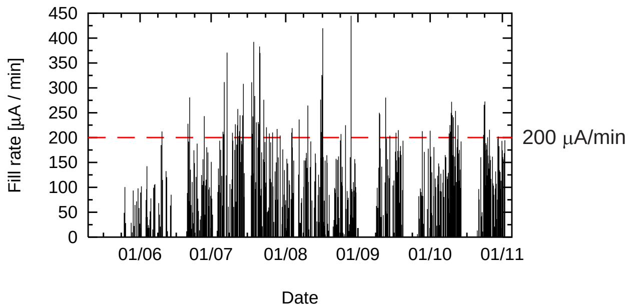

Figure 5: Effective rate of filling during the 1998 run. The dashed line indicates the typical filling rate of 200 µA/min.

The filling rate for 1998 can be summarized as:

- Best observed: 400 µA/min
- Typical: 200 µA/min
- From the SPS: 550-750 µA/min

We note that even for the best examples only about 50-60% of the available beam rate from the SPS was used. The typical filling rate was about 30% of the rate available from the SPS.

Part of the observation can be explained by the SPS not always being optimally tuned (appearance of the so-called “ghost” etc.) and delivering less than optimal beam. Apart from that a problem of clearly sub-nominal injection efficiency occurred in LEP for the 1998 run. The injection efficiency will be discussed in the next section.

2.3.Problem of Injection Efficiency

The scheme of the LEP injection has been described in detail in the literature (e.g. [1] and [2]). We summarize its basic idea as illustrated in Figure 6.

1. An off-energy beam is injected horizontally into LEP, moving it as close as possible towards the septum. The septum is adjusted such that the beam offset at the kicker IK3 is $\Delta x = D_x \cdot \Delta p/p$ with the horizontal dispersion D_x and the relative energy offset $\Delta p/p$. Thus the beam is injected on axis in betatron space.
2. The IK3 kick is adjusted in order to empirically close the injection oscillation.
3. The IK2 and IK1 kickers are adjusted in order to create a closed AC bump for the stored beam.

Along the injection path a regular focusing lattice is installed (see Figure 6). The details of the injection process therefore depend on the beam optics.

The injection scheme shown in Figure 6 worked well during 1997, providing a 95% injection efficiency. This performance could not be repeated in 1998 with efficiencies between 30% and 60%. It was observed that it was not possible to simultaneously close the injection oscillation and the AC bump. This problem affected both

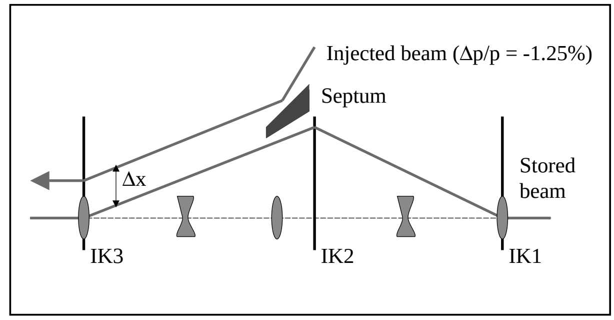

Figure 6: Principle of LEP accumulation. A septum and three kickers are used for the setup of accumulation.

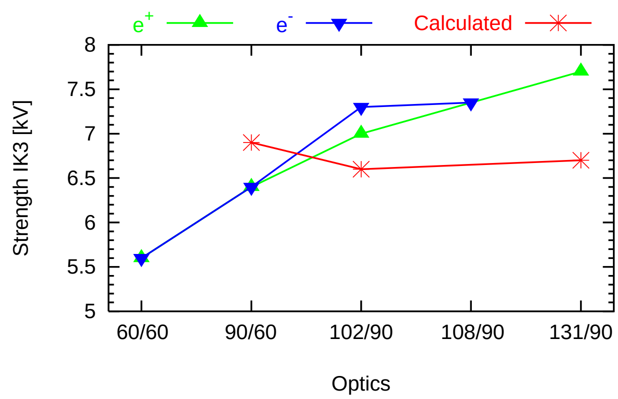

Figure 7 Strength of required IK3 kick for different optics. Measured data is compared to the calculation.

types of particles, making a misalignment problem very unlikely. The only major change between 1997 and 1998 was the change in the horizontal phase advance from 90° per cell to 102° per cell (a change in vertical phase advance from 60° to 90° should have no effect).

Several studies have been performed in order to exclude a number of possible problems:

1. Check of energy offset.
2. Check of injection steering from the SPS to LEP.
3. Check that RF frequency offset of +100 Hz at injection did not cause any problems.

Those studies did not provide a solution to the problem of low injection efficiency. The suspicion remained that the problem was related to the horizontal phase advance in the injection region. Figure 7 shows that a systematic increase in the strength of the required IK3 kick has been observed. Note that the 60/60°, the 102/90° and the 131/90° measurements are all from 1998. The theoretical expectation [7] is also indicated in Figure 7. It is seen that no increase of the IK3 kick is expected. The LEP data is in clear contradiction to the expectation.

We note that the calculation predicts a loss of 1σ in separation between the injected and the circulating beam for the change in optics from 90/60° to 102/90°. The available relative clearance is expected to be reduced from 4.2σ to 3.3σ. This should still be sufficient for a good injection with about 0.1% loss per injection.

Summarizing, we conclude that we expect a reduction in beam separation with the 102/90° optics. This change should be sufficiently small in order to allow injection efficiencies above 90%. The used model of injection might, however, be incomplete. The empirically found IK3 kicks show a systematic increase with horizontal phase advance for both electrons and positrons. This is in contradiction with the calculation that even predicts a decrease of the IK3 kick when going from the 90/60° to 102/90° optics. Further studies are required in 1999 in order to solve the problem of low injection efficiency. With a 95% injection efficiency one could expect to shorten the typical filling time from 20 min to 10 min. This corresponds to a gain of roughly 3% in integrated luminosity.

3 MAXIMUM BEAM INTENSITY FOR 1999

In the previous sections it was shown that LEP injection in 1998 reliably supported beam currents above 750 μA per bunch. At this value a hardware limitation from certain RF cables was encountered. The RF cables are being replaced and it is expected that the LEP hardware allows bunch currents of at least 1 mA in 4 bunches for 1999 [8]. Here we discuss the maximum bunch current from the beam physics and operations point of view. Results from specific machine experiments are reviewed.

3.1. Basic Limitations

It is beyond the scope of this paper to fully review the basic limitations of injection and beam current for LEP. This topic has been extensively studied and is well covered in literature (see for example [9] and [10]). We quickly mention the most important limitations for LEP.

Transverse Mode Coupling Instability

The threshold current I_{th} for appearance of the transverse mode coupling instability (TMCI) is given by [11]:

$$I_{th} = \frac{2\pi E \, f_{rev} Q_s}{e \sum \beta \, k_\perp(\sigma_s)}$$

Here, E is the beam energy, f_{rev} the revolution frequency, Q_s the synchrotron tune, e the electron charge and β the betatron function at the sources of transverse impedance $k_\perp$. Note that the impedance $k_\perp$ depends on the bunch length σ_s that in turn is influenced by the value of Q_s. In order to increase the threshold current for a given optics it is desirable to increase the injection energy, to increase the value of Q_s and to decrease the transverse impedance. The measures mentioned in Section 1 were partly aiming at reducing the TMCI threshold.

It will be shown that the TMCI limit was established at 1030 μA per bunch in 1998. The transverse impedance will increase by about 1.5% in 1999 with respect to 1998. Therefore about the same TMCI threshold as in 1998 can be expected for 1999.

It is important to realize that the TMCI threshold is a single beam threshold. For LEP physics runs two beams are simultaneously filled. The encounter of an electron bunch with the positron bunches at locations of vertical beam separation leads to a residual interaction involving the impedances as well as direct fields. It has been shown that a reduction of about 12% in the TMCI threshold can be expected for 4 on 4 bunches [12].

Synchro-Betatron Resonances

Synchro-betatron resonance are more severe in the vertical than in the horizontal plane. They occur if the following condition is fulfilled:

$$Q_v = n \cdot Q_s \qquad \text{with} \quad n = 1, 2, 3$$

Here, Q_y is the vertical betatron tune. Note that the above condition applies for both coherent and incoherent tunes. Q_y and Q_s need to be adjusted such that synchro-betatron resonances are avoided for highest intensities, though it is possible to cross those resonances at low to medium bunch intensities.

Longitudinal Single Bunch Instability

This instability is not completely understood. For short bunches and high intensities a longitudinal quadrupole mode and a subsequent saturation of bunch current are observed. The instability is avoided by increasing the bunch length at injection.

3.2. Standard 1998 Working Point

The machine settings that were used as the standard working point (SWP) for LEP injection in 1998 are summarized in Table 2.

Table 2: Overview of machine settings for the standard working point (SWP) and a new high Q_y working point (New WP) of LEP injection.

Parameter	**SWP**	**New WP**
Q_x (50 μA/bunch)	0.28	0.29
Q_y (50 μA/bunch)	0.23	0.30
Q_s (50 μA/bunch)	0.132	0.142
Chromaticities	1-2	0.5-1

The tune settings are defined for a bunch current of 50 μA for which they can be measured reliably. The listed tune settings are therefore close to the incoherent tunes. For high intensities the coherent tunes will be significantly lower than the values listed in Table 2. The LEP strategy has been in 1998 to adjust the tunes only at 50 μA and to keep the incoherent tunes constant from then onwards. The resulting evolution of the coherent tunes as a function of intensity is shown in Figure 8 for the standard working point.

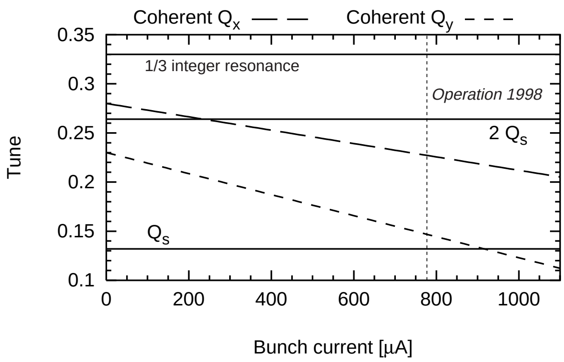

Figure 8: Evolution of coherent horizontal and vertical tunes as a function of beam intensity (standard working point). The incoherent tunes are assumed to be constant. The synchro-betatron resonances and the 1/3 integer resonance are indicated as well.

The incoherent tunes Q_x and Q_y are located above and below the $2Q_s$ resonance. As beam is accumulated the coherent Q_x crosses the $2Q_s$ resonance at relatively low currents. The maximum reach in current is limited due to Q_y approaching the Q_s resonance. This working point routinely allowed accumulating more than 750 µA for 4 on 4 bunches and standard LEP operation.

The SWP has been extended to 940 µA per bunch during machine development [13]. In order to reach this high bunch current the Q_y was raised during accumulation. Thus the coherent tune was moved away from the Q_s resonance. However, at the same time the incoherent tune was moved towards the $2Q_s$ resonance. Due to this mechanism the maximum bunch current for the SWP is limited at about 940 µA from synchro-betatron resonances. Machine studies revealed no reduction due to separators or the presence of the other beam. This observation is consistent with the TMCI limit not being reached.

3.3. High Q_y Working Point

In order to reach bunch intensities above 940 µA a new working point for injection has been tested in 1998 [14]. It has been shown in 3.2. that the standard working point is limited due to:

1. the coherent Q_y reaching the Q_s resonance from above
2. or the incoherent Q_y approaching the $2Q_s$ resonance from below.

The new working point moves the incoherent vertical tune above the $2Q_s$ resonance thus providing more space for the coherent vertical tune. The machine settings are summarized in Table 2. Figure 9 shows the evolution of the coherent tunes as a function of bunch intensity.

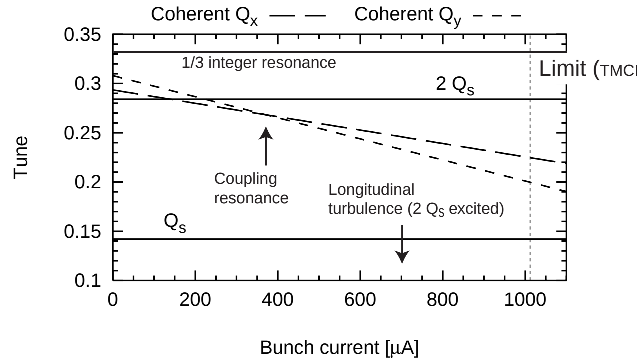

Figure 9: Evolution of coherent horizontal and vertical tunes as a function of beam intensity (high Q_y working point). The incoherent tunes are assumed to be constant. The synchro-betatron resonances and the 1/3 integer resonance are indicated as well.

Both horizontal and vertical incoherent tunes are above the $2Q_s$ resonance, but below the 1/3 resonance. As beam is being accumulated, the coherent tunes cross the $2Q_s$ resonance and also the coupling resonance. At highest bunch currents the coherent tunes are both well separated from synchro-betatron resonances and it is possible to reach the TMCI limit. In fact with this working point the TMCI limit was reached at 1030 µA per bunch in a single beam study during 1998 [14]. Studies of higher Q_s working points ($Q_s > 0.144$) are inconclusive at this time but could provide for a further increase of the TMCI threshold.

The crossing of the coupling resonance can impose a problem for LEP operation. The Q-loop requires that Q_x and Q_y are well separated. The high Q_y working point does therefore not directly work at bunch intensities below 400 µA. Also, as the coherent tune shift scales with one over the beam energy the high Q_y working point requires some special precautions during the energy ramp [5].

3.4. Q_s Constraints

The choice of working points is complicated by constraints in the possible values of Q_s. The use of synchrotron double-batch injection at LEP together with the required “cog-wheeling” in the injector chain imposes some constraints on Q_s [1]:

1. Due to hardware and cog-wheeling requirements the difference between the first and second batch injected into LEP must be:

$$(6 + i \cdot 7) \text{ LEP turns}$$

2. In order for double batch injection to work the synchrotron phase ϕ between the two batches should be around π (with the first batch at zero phase):

$$2/3\,\pi < \phi - n \cdot 2\pi < 4/3\,\pi$$

3. With $\phi = 2\pi\,(6 + i \cdot 7)\,Q_s$ we get the following condition for Q_s:

$$1/3 < [\,(6 + i \cdot 7)\,Q_s\,] < 2/3$$

The square brackets indicate that only the non-integer part of the number is to be considered. It is immediately seen that the above condition is false for $Q_s = 1/7$ and all values of i. The injection scheme results in a hole in feasible Q_s values [1, 15]. The hole is shown in Figure 10 for different delays in LEP turns between the two batches (different i in above formulae).

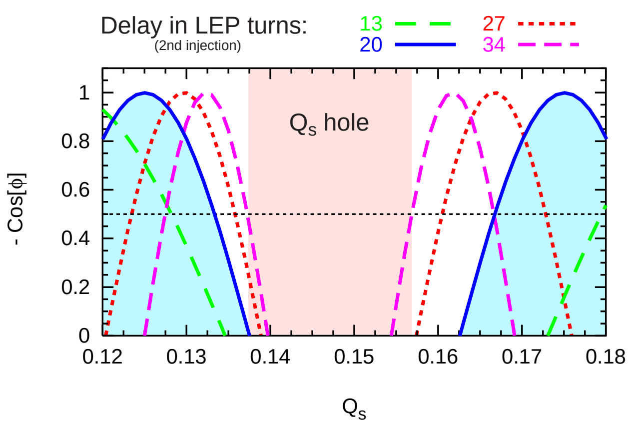

Figure 10: Cosine of synchrotron phase between first and second injected batch. For double batch injection to work the Cosine of the phase must be above 0.5.

The Q_s hole can be reduced but never eliminated for longer delays (larger i). There is also some maximum allowable delay between the two batches due to synchrotron radiation in the SPS and filamentation in LEP [1].

There might be a possibility to avoid the appearance of the Q_s hole. It does appear because the initial delay of 6 turns is close to 7. If the initial delay is chosen to be 10 or 11 LEP turns then the Q_s hole will be shifted and can also disappear. There is some freedom in the adjustment of the initial delay between the first and second injected batch (it had been changed from 8 to 6 in 1996). Studies are ongoing in order to see whether a solution can be found.

4 FEEDBACK SYSTEMS

The LEP feedback systems have been described in [16]. Here we shortly review the requirements for the feedback systems as they arise in injection and accumulation.

4.1. Longitudinal Feedback System

The longitudinal feedback system has been used extensively during the 1998 run. The system was mandatory in order to reduce the longitudinal excitation of the beam. Without it early saturation in beam current and sudden beam losses have been observed. The longitudinal feedback is required to work reliably and accurately in 1999.

4.2. Transverse Feedback System

The transverse feedback system has not been used during LEP operation in 1998. This can be partly explained by the fact that the injected beam current was not reaching the TMCI limit where the transverse feedback is most helpful for LEP. The LEP transverse feedback operates in resistive mode, thus allowing to lower the chromaticity by 1-2 units. Note that lower chromaticities have already been used for the high Q_y working point in order to reduce the m = -1 signal. The transverse feedback will in addition result in less sensitivity to changes of chromaticity during the energy ramp from 22 GeV to ~100 GeV.

As the transverse feedback at LEP has not been operational yet for both planes and both beams, its preparation for the 1999 run requires special attention. The possible problem of an incompatibility with the Q-loop has been studied and a workable solution has been found [17].

5 CONCLUSIONS

The injection and accumulation systems supported the excellent LEP performance in 1998, providing the highest operational LEP beam currents ever. Total beam currents of 6 mA were achieved routinely with a self-imposed limit from the heating of certain RF cables.

Filling and accumulation typically required 20 min. This time can roughly be halved if a problem in injection efficiency during 1998 can be understood and fixed for the 1999 run. Studies are ongoing. On average 25 min per physics fill were lost at injection due to problems in the injector chain, the LEP equipment and the LEP RF system. Improvements would directly result in a better integrated luminosity.

The different working points for LEP injection have been discussed. The 1999 injection setup should initially use the standard working point from 1998. It allows easy and stable accumulation up to about 800 μA per bunch and offers a simple solution for the energy ramp. It will also work fine for low currents during the start-up. If bunch currents are being pushed above 800 μA then either the standard working point is used with a slightly more complicated operational procedure or the high Q_y working point is commissioned. For highest beam currents the high Q_y working point offers greater stability and simplicity (constant incoherent tunes) and a larger maximum intensity. It should allow maximum bunch currents between 950 μA and 1000 μA with 4 on 4 bunches.

The expected limitation is the transverse mode coupling instability with residual beam-beam effects.

The choice of the working point is limited by a hole in the feasible Q_s values. This hole limits the operational freedom at injection. Studies are underway in order to determine whether the Q_s hole can be closed.

The longitudinal feedback is essential for the 1999 high current running. The transverse feedback will potentially be very useful if the intensities during routine operation approach the transverse mode coupling instability.

6 ACKNOWLEDGEMENTS

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