Review of High Energy e^+e^- Colliders

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Abstract

The performance of TRISTAN, the e^+e^- collider at KEK, the National Laboratory for High Energy Physics, Tsukuba, Japan, and of LEP, the e^+e^- collider at CERN, the European Laboratory for Particle Physics, Geneva, Switzerland, is reviewed in terms of average and peak circulating current, average and peak luminosity, achieved vs. scheduled operating hours, ratio between machine development and colliding-beam physics runs. Critical issues, such as control system features, reliability, reproducibility, and their effects on the performance of TRISTAN and LEP are discussed. The following accelerator physics topics are presented: beam-current limitations, beam-beam effects, polarization, energy calibration. The discussion includes a description of the phenomena observed and of the cures applied. The improvement programmes are discussed. In TRISTAN the conversion into a photon factory is foreseen. The improvement programme for LEP includes an energy upgrade to energies beyond the threshold of W pair production, a luminosity increase by nearly an order of magnitude at the Z^0 energy by storing up to 36 bunches in each beam, and increasing the level of transverse polarization.

1 INTRODUCTION

Last year, LEP has been operated from 9 April to 11 November with scheduled interruptions. It is just about to be operated again this year. TRISTAN was operated from 6 February to 8 July, and again from 8 October to 20 December 1991, also with scheduled interruptions. This year, TRISTAN started on 21 February. Their performance is discussed in Chapter 2. Accelerator physics aspects are presented in Chapter 3. Plans for their development in the future are discussed in Chapter 4. Earlier performance reviews were published in [1, 2] for LEP, and in [3, 4] for TRISTAN, respectively. Workshops on LEP Performance were held at Chamonix, France, in 1991 and 1992 [5, 6].

The key parameters of LEP and TRISTAN are compiled in Table 1. The typical operating energy of LEP is almost twice that of TRISTAN. Since the bending radius in LEP is more than an order of magnitude larger than that in TRISTAN, the synchrotron radiation losses are actually higher there than in LEP by about a factor of two. These high losses result in a very small horizontal damping time and a larger horizontal emittance and energy spread in TRISTAN. The betatron tunes are about twice as large in LEP, while the synchrotron tunes, the β-functions at the interaction points and the bunchlengths are very similar. The peak currents are the sums of the e^+ and e^- currents in both cases. They should be compared to a design current of 6 mA for LEP [7], and a maximum current of 20 mA assumed for the design of TRISTAN components [8]. The peak 1991 luminosities should be compared to design luminosities of 14 $\mu b^{-1}s^{-1}$ for LEP, and 20 $\mu b^{-1}s^{-1}$ for TRISTAN, including a factor of two improvement by the mini-β insertion.

Table 1: Typical Parameters

	LEP	TRISTAN
First operation	Aug 89	Nov 86
Typical energy/GeV	45.6	29
Bunches/beam	4	2
Peak current/mA	3.7	14.5
Peak luminosity/$\mu b^{-1}s^{-1}$	10	37
Circumference/m	26658	3018
Bending radius/m	3096	246.5
Synchrotron loss/MeV	126	253.5
Hor. damping time/ms	64	1.1
Hor. tune	70.24	36.62
Vert. tune	76.19	38.72
Synchrotron tune	0.085	0.11
Hor. β-function/m	1.25	1.00
Vert. β-function/m	0.05	0.04
Hor. emittance/nm	36.8	80
Bunchlength/mm	14	15
Energy spread/10^{-3}	0.72	2.33

2 CURRENT PERFORMANCE

2.1 *Statistics from Operation*

Operational statistics for LEP and TRISTAN during the year 1991 are displayed in Table 2. Since the statistics for the two machines are not produced in the same manner, empty entries are inevitable. For LEP, setting-up and machine development MD are accounted separately. It is also known during what fraction of the physics time the beams were in coast, i.e. colliding at the operating energy. For TRISTAN the figures for the first and second half year are shown separately, because of the modifications to the machine which were installed during the summer. Their net effect was an increase of the average luminosity in TRISTAN by about a factor of two. On a good day, the beams are in collision for more than 75% of the physics time. The average luminosities in LEP and TRISTAN are about 1/6 and 1/5 of the peak luminosities, respectively.

Table 2: Statistics of Operation in 1991

	LEP	TRISTAN	
Months	4-11	2-7	10-12
Total/h	4002	1859	1435
Setting up/h	243 }	855	291
MD/h	997 }		
Physics/h	2762	709	849
Actual Coast/h	1242		
Coast/Physics/%	45		$\approx$ 75
Failures/h	1000	295	295
Av. luminosity/$\mu b^{-1}s^{-1}$	1.7	3.8	7.9
Int. luminosity/pb^{-1}	17.3	9.6	24

A typical LEP or TRISTAN cycle consists of filling the machine and of the coast with the beams in collision. Filling the machine involves a gap for cycling the magnets, injection at 20 or 8 GeV, ramping the energy to about 46 or 29 GeV, decreasing the amplitude functions β at the experimental interaction points from the injection to the operating value (this now happens during the ramp in LEP).

For the average LEP physics run in 1991, the filling time was 3:08 h, the coast time was 8:00 h, and mean fault time was 6:32 h. The filling time is much longer than that assumed in the design, 0:20 h. The downtime is about 25% of the scheduled time. Because of better vacuum and smaller losses due to beam-beam bremsstrahlung, the beam lifetime is much better than assumed in the design. It made possible longer coast times than foreseen in the design, 2:00 h. The long fill and fault times imply that much remains to be done in order to improve the availability, reliability and reproducibility of LEP. No single phenomenon explaining most of the fault time has been found. Three years of operational experience with LEP are discussed elsewhere during this conference [9]. The average total beam current at the start of the coast was 2.8 mA, which corresponds to 76% of the peak value, and to 47% of the design value.

In TRISTAN, the mean filling time is about 0:45 h, and the mean coast time is about 2:00 h. The beam lifetime is about 4:00 h, rising slowly while the beam currents decay. The down time is about 20% of the scheduled time. On a good day, the average total beam current at the start of the coast was 12 mA, which corresponds to 83% of the peak current, and to 60% of the maximum current assumed for the design of TRISTAN components.

2.2 *Integrated Luminosities*

The integrated luminosities for LEP and TRISTAN in 1991 are summarized in Table 3 for all experiments separately, as well as their mean values and standard deviations. For LEP, the difference is now much smaller than in 1990 when it was 10%. Early in 1991, a few superconducting insertion quadrupoles were realigned after they had been found to be misaligned by a few cm along the beam axis inside their cryostats.

In LEP, the integrated 1991 luminosity is more than a factor of two higher than that in 1990, 8.6±0.9 pb^{-1}. The best day had an integrated luminosity of 320 nb^{-1}. During a good fill, the experiments collect about 6000 Z^0's each. The improvement in luminosity is believed to be due to a change of the integral parts of the tunes from $(Q_x, Q_y) = (71, 77)$ to $(70, 76)$, found by beam-beam simulations. The vertical tune Q_y close to a multiple of four made LEP much more sensitive to various errors. However, these difficulties were eventually overcome, e.g. by changing the polarities of electrostatic separators such that the effects of diametrically opposite ones cancel, and by not using skew quadrupoles inside vertical separator bumps while they are excited.

Table 3: 1991 Integrated Luminosities in pb^{-1}

LEP		TRISTAN	
Exp.	Int. L	Exp.	Int. L
Aleph	17.4	Venus	36.9
Delphi	17.2	Topaz	29.8
L3	17.6	Amy	34.1
Opal	16.9		
Mean	17.3±0.3	Mean	33.6±3.6

In TRISTAN, the integrated 1991 luminosity is higher than that in 1990, 27.2±4.1 pb^{-1}, showing the effect of the mini-β insertions. The best day had an integrated luminosity of 1.0 pb^{-1}. Superconducting quadrupoles had been installed before the run in the first half of 1991, reducing the β-functions at the interaction points by a factor of two. Rotational misalignments of these quadrupoles by up to 18.5 mrad were detected by measurements with beam, and corrected by April 1991. At the same time, a coil breakdown of a conventional quadrupole near the Nikko experimental area was repaired. Still, conditions for colliding-beam physics were not good. This was eventually traced to be due to the method used for the correction of the coupling due to the solenoidal fields of the detectors. This method used perturbation theory to compute the strengths of the skew quadrupoles used for the correction, assuming that the normal orbit functions remain unchanged. The new method – "Perfect Matching", – does not make that assumption any longer, but simply computes the strengths of both normal and skew quadrupoles in the neighbourhood of the interaction points to satisfy all matching conditions at the same time. In this manner, the dynamic aperture was increased. Before the run starting in October 1991, another set of skew quadrupoles was added next to the superconducting quadrupoles. It reduced the strengths of the other skew quadrupoles and increased the dynamic aperture further.

3 ACCELERATOR PHYSICS

3.1 Beam Current Limitations

In LEP, the current in single bunches is limited to about 0.65 mA by the Transverse Mode Coupling Instability (TMC) [10] which is caused by the interaction of the particles in the bunch with its own short-term wakefield. The threshold of this instability is reached when the frequency of the $m = 0$ mode, which decreases with the bunch current coincides with the frequency of the $m = -1$ mode which is fairly independent of the bunch current. Results of measurements of these frequencies are shown in Figure 1. They are in reasonable agreement with predictions. It is hoped to raise the TMC threshold this year by exciting wiggler magnets to lengthen the bunches and/or by increasing the synchrotron tune Q_s.

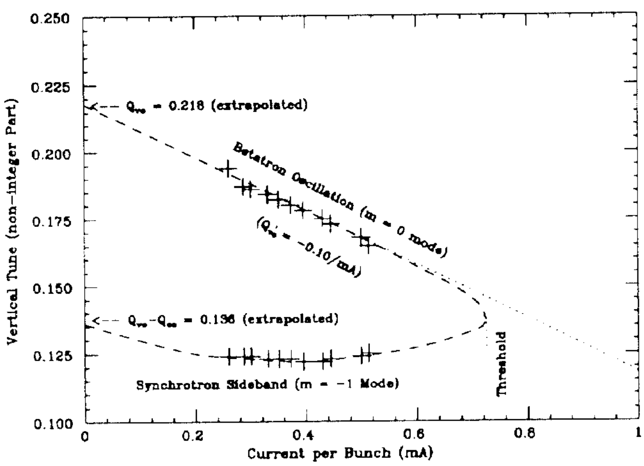

Figure 1: Frequencies of TMC modes in LEP

In TRISTAN, the TMC threshold is above the maximum bunch current of 5 mA. Current limitations arise from synchro-betatron resonances, the design of the higher-order mode couplers of the superconducting RF cavities, and a catastrophic pressure increase.

3.2 Beam-Beam Effects

A quantitative measure of the beam-beam effect are the linear beam-beam tune shift parameters ξ_x and ξ_y. They can be obtained experimentally in two different ways.

In LEP, the beam-beam tune shift parameters ξ_x and ξ_y are obtained by solving the standard equations:

$$\xi_y = \frac{2er_e L\beta_y}{I\gamma} \qquad \xi_x = \frac{Nr_e}{2\pi\gamma\epsilon_x} \tag{1}$$

All quantities on the right hand side of the equation for ξ_y have their conventional meaning and can be measured. The assumption that the vertical rms beam radius σ_y is much smaller than the horizontal one σ_x is justified. In the equation for ξ_x, the horizontal emittance $\epsilon_x = \sigma_x^2/\beta_x$ can either be measured with synchrotron light monitors or assumed to stay at its nominal value independently of the bunch population N. The accumulated results for all physics runs in 1991 are displayed in Figure 2. A saturation happens in the neighbourhood of $\xi_y = 0.02$, with a large scatter of the observations between 0.01 and 0.03. Further analysis of the variations of the luminosity L, and of L/I and L/I^2 with the current I in one beam shows that L/I varies less with I than the other quantities, indicating that LEP is indeed at the beam-beam limit [11].

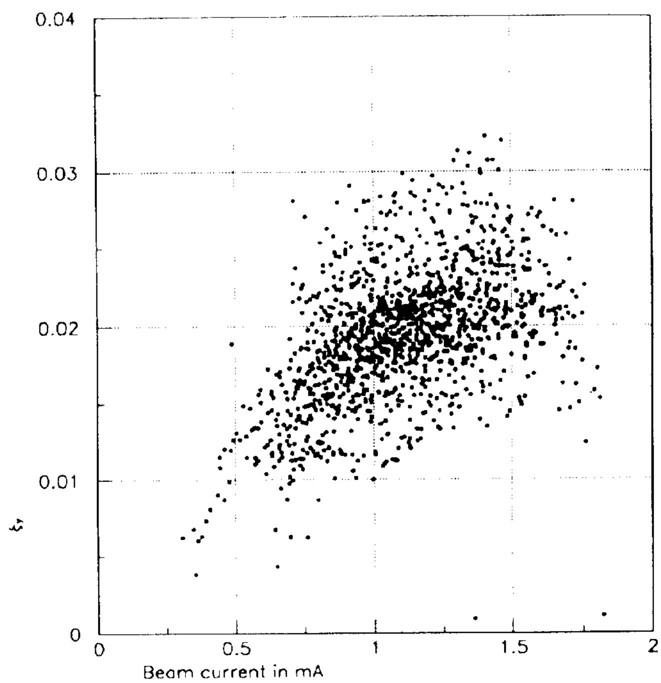

Figure 2: Vertical Beam-Beam Tune Shift Parameters ξ_y for all 1991 LEP Physics Fills vs. Current in one Beam

In TRISTAN, both beam-beam tune shift parameters are obtained by observing the frequencies of the coherent beam-beam modes [12]. By mixing beam position monitor signals the response to the modes with the smallest and largest frequency shift is enhanced while the response to the remaining modes is reduced [13]. Repeating frequency scans and calculation a few times in a minute generates a display of luminosity and beam-beam tune shift parameters. The response is fast enough to use it for optimizing the luminosity. An example is shown in Figure 3. No saturation is observed up to the observed maximum value $\xi_y \approx 0.03$, which does not include the Yokoya factor [14] and therefore overestimates ξ_y by about a factor of 4/3. However, a reduction of the lifetime is observed.

3.3 Polarization

In TRISTAN, a polarization level of about 40% has been observed earlier [15]. Recent data are presented elsewhere at this conference [16]. The polarization time is only about two minutes at 29 GeV. Polarization studies foreseen this year include the following subjects: (i) R&D for a fast multi-photon polarimeter similar to the one installed in LEP. (ii) high resolution polarization measurements dur-

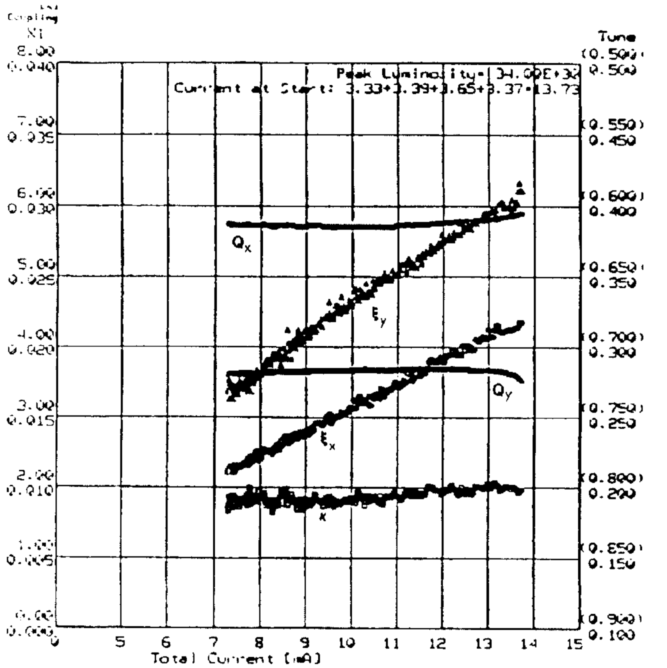

Figure 3: Beam-Beam Tune Shift Parameters ξ_x and ξ_y, Tunes Q_x and Q_y, and Coupling κ for a TRISTAN Fill vs. Total Current

ing the physics run, (iii) a fine scan of polarization vs. energy, investigating the following depolarizing mechanisms: closed orbit distortions, dispersion, solenoid fields, beam-beam interaction, energy spread, (iv) compensation of depolarizing effects by harmonic spin matching, (v) a precise energy calibration using depolarizing resonances.

In LEP, the first observation of transverse polarization in 1990 [17] was repeated in 7 out of 8 runs in 1991 [18]. The observed degree of polarization, up to 18%, is in fair agreement with computer simulation results using the rms vertical orbit errors actually observed. The aims of the polarization MD in LEP this year are as follows: (i) find polarization in 90° physics lattice at physics energy, (ii) commission the extra polarization wiggler magnets which reduce the polarization time from 310' to 36' [19], (iii) compensate the solenoids with small spin rotators, (iv) calibrate the energy at the end of physics fills, (v) improve the degree of polarization. The similarity with the TRISTAN polarization programme is striking.

3.4 *Energy Calibration*

The main aim of the LEP polarization runs in 1991 was an energy calibration to better accuracy than can be achieved by magnetic measurements alone. A good fraction of the present experimental error on the mass and width of the Z^0 is now due to the LEP energy calibration. The results of the runs are summarized in Table 4. The figures shown already include a correction for the temperature variation of the dipoles of up to 1 MeV. The jump in energy observed on 11 November 1991 shows the effect of hidden variables.

Table 4: Results of 1991 LEP Energy Calibrations. $E_{\rm p}$ and $E_{\rm fd}$ are the energies from depolarization and field display. The synchrotron tune is always $Q_s = 0.083$.

Date	Q_x	Q_y	$E_{\rm p} - E_{\rm fd}$ MeV
16.09.	70.136	76.203	−38.1±1.2
02.10.	70.140	76.203	−32.5±1.2
26.10.	70.137	76.2014	−30.4±1.2
11.11./2am	70.1389	76.2113	−37.2±1.6
11.11./7am	70.1358	76.2014	−34.2±1.2

4 PLANS FOR THE FUTURE

4.1 *Plans for LEP*

Change of Tune The tunes will be raised by some 20 units beyond the values used earlier, by increasing the phase advances in the regular cells in the arcs from 60 to 90°. Their exact values have been chosen such that they simultaneously satisfy the constraints imposed by regular operation for physics and for the future developments. It should thus be possible to reduce the number of transients between different optical configurations, and to keep the beam at the beam-beam limit down to lower currents, because the equilibrium emittance is reduced by about a factor of three.

Luminosity Increase A long-term luminosity increase with up to 36 bunches in each beam has been studied [20]. Meanwhile, a "Crash Pretzel Programme" has been started [5]. Electrostatic separators with horizontal fields, recuperated from the Sp$\bar{\rm p}$S collider and installed around all even LEP pits, cause horizontal orbit distortions of opposite sign for e^- and e^+ in all arcs, avoiding beam-beam collisions there. Doubling the number of bunches is possible without substantial upgrading of machine components and with relatively minor changes to the experiments. The problem with the sparking rate of the separators was solved by always having one plate at positive potential and the other one at ground potential. Experiments with combinations of electrostatic and magnetically simulated pretzel orbits were very satisfactory [21]. It is expected that pretzels with eight bunches in each beam will be operational towards the end of 1992. After the completion of the LEP energy upgrade, the number of bunches in each beam will be increased by a factor up to 9 at the Z^0 energy, and by a factor 2 − 3 above the W threshold, increasing the luminosity by similar factors.

Energy Upgrade The Energy Upgrade Project will raise the LEP beam energy beyond the W pair production threshold. Its physics aim is the production of 8000 W pairs. At 90 GeV, where the W pair production cross section is 16 pb, this requires an integrated luminosity of 500 pb^{-1}. If LEP is in coast during 10^4 hours, a mean luminosity of 14 μb^{-1}s^{-1} is needed. The installation schedule for the superconducting (s.c.) RF cavities is shown in

Tab. 5. The maximum beam energies assume that both Cu and s.c. RF systems are used, and that the average voltage gradient in the s.c. system is 5 MV/m. The status of the energy upgrade programme is as follows [22]: The eight installed cavities reached 70% of the design gradient 5 MV/m. Twenty Nb cavities are at CERN, 160 Nb-sputtered Cu cavities have been ordered. Circulators, 1.3 MW klystrons, waveguides, electronics, etc. are defined and mostly ordered. The klystron gallery near Pit 8 has been excavated, that near Pit 4 will be finished in early 1993. The 6 kW refrigerator has been installed in Pit2, the other refrigerators have been ordered. Tests of a LEP lattice with 90° phase advance are well advanced [23]. New straight sections for operation up to almost 100 GeV have been designed, their installation is foreseen in early 1993. Upgrades of cooling, ventilation, power, etc. are under way.

Table 5: Schedule of the LEP Energy Upgrade

Year	Number of s.c. cav.	E_{max} GeV
1992	12	59
1993	64	77
1994	192	87

Polarization For precise tests of the Standard Model at the Z^0 peak the LEP physics community has asked for longitudinally polarized beams at the LEP experiments. A study of the implications was completed in 1991 [24]. Spin rotators of the Richter-Schwitters design rotate the spin by an asymmetric system of vertical bends. The contribution of the spin rotators to depolarizing resonances has been shown to be much smaller than that of the errors in LEP without spin rotators. A longitudinal spin physics programme might be launched for installation after the completion of the W physics programme.

4.2 *Plans for TRISTAN*

Since 1990, TRISTAN is in its second phase of operation, aiming for an integrated luminosity of 300 pb^{-1} within 3 to 4 years rather than the highest energy possible. The beam energy was chosen at 29 GeV, such that there is enough margin in the RF system to operate at full current and minimum horizontal emittance even when a few RF cavities are not operational. With the best luminosity observed in 1991, $L = 1$ pb^{-1}/day, this phase of TRISTAN operation will take about 300 "good days".

Later on, TRISTAN will be converted into a fourth-generation light source with high brilliance, by increasing the phase advance in the arcs and by installing damping wigglers in the downstream halves of the straight sections.

5 CONCLUDING REMARKS

Two machines were considered in this review, TRISTAN which was operated from November 1986, and LEP from August 1989. TRISTAN reached a steady state of operation in the second half of 1991, with good average and peak luminosities, after the installation of mini-β insertions with superconducting quadrupoles in the first half of 1991. The peak LEP performance in current and luminosity is within better than a factor of two of the design values. However, the average performance is much below the peak performance. The availability, reliability and reproducibility need to be improved. There is no dramatic current limitation in TRISTAN. It is hoped that the transverse mode coupling threshold in LEP will be raised in the future. TRISTAN will be operated as a high-energy e^+e^- collider for a few more years at high luminosity, and will then be converted into a synchrotron light source. For LEP, the luminosity increase, the energy upgrade and longitudinal polarization will provide an attractive physics programme up to the end of the 1990's.

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