FOUR DECADES OF COLLIDERS (FROM THE ISR TO LEP TO THE LHC)

S. Myers, CERN, Geneva, Switzerland

Abstract

I briefly describe CERN's colliders starting with the ISR, going through LEP, and finishing with the LHC. I describe the incredible impact on accelerator physics of the almost forgotten, first ever hadron collider, the ISR. I also describe the 12 years of operation of LEP. Finally I provide the latest results of beam operation in the LHC as well as the plans for the near and far future.

THE ISR

The ISR was constructed during the period 1966 to 1970 and was operated from 1971 to 1983 for physics (see review articles in [1], [2]). The combined-function magnet lattice formed two independent, interleaved rings, intersecting in eight points, five of which were used for experiments. A view of the ISR at intersection point 5 is shown in Figure 1.

The circumference of the orbits was 943m, exactly 1.5 times the circumference of the PS.

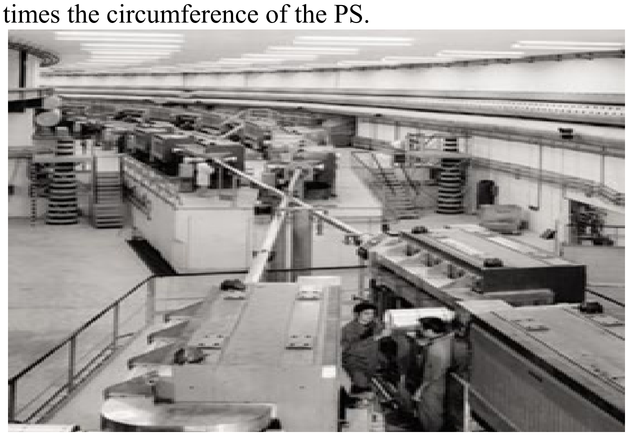


Figure 1: Interaction point 5 in the ISR.

Stacking

The accumulation of the very high currents in the ISR relied on a process called momentum "stacking" [3]. A stack was built by accumulating a few hundred PS beams across the large momentum aperture of the ISR. A single cycle involved RF capture of the PS 20 bunches at the injection momentum orbit of -2% and accelerating this beam (by changing the RF frequency) to a momentum orbit of +2%. When the beam reached its required $\Delta p/p$, the RF was switched off and the beam debunched. The maximum single beam current was 57Amperes.

Phase Displacement

Phase displacement occurs when an RF bucket traverses a debunched beam .The particles in the debunched beam travel around the unstable trajectories associated with the bucket (outside the separatrix). Traversing a debunched beam from high momentum to low momentum produces an increase in the average momentum of the debunched beam by an amount equal to the phase space area of the phase displacing buckets. A good analogy is to release droplets of mercury into a cylindrical container containing some water. The mercury droplets go from high energy to low energy and the water energy is increased.

Since the ISR circumference was larger than the PS, the maximum energy was also higher (31.4 compared to 26.6GeV). In the never-ending quest for higher beam energies, it was decided to attempt to increase the energy of the accumulated beam in the ISR. However the small ISR RF system could not capture a beam with 3% momentum spread. So in our relative ignorance of the problems (space charge changing tunes, chromaticity, orbits, RF noise effects, absence of diagnostics...) we decided to attempt to phase displace high intensity stacks of protons. Initially the progress was slow but after some better understanding and a few break-throughs, 31.4GeV became the preferred high luminosity operational energy of the ISR [3].

Working Lines and Space Charge Compensation

The ISR had a working **line** not a working point. The required large tune spread resulted from the stability requirement from chromaticity and the large momentum spread needed for beam stacking. The minimum tune range of around .07 (see Figure 2) created difficulties to find an area in the tune diagram which would allow the coasting beam to be free of low order non-linear resonances. The working line drawn in Figure 2 had the stacked beam between the 3rd and 5th order resonances but necessitated traversal of the bunched beam across the family of 5th order resonances. It was well known that the space charge tune shift caused a "sagging" of the working line, rather like loading a beam with heavy weights. This had two effects, resonances (in Figure 2 the beam would reach the main coupling resonance), and beam instabilities caused by the reduction of the chromaticity for the low momentum part of the stack. In order to be able to compensate the space charge effect we had (of course) to measure it. Here is one of the major problems with unbunched beams; lack of diagnostics. A complicated system was developed which used beam transfer functions of empty buckets to measure the working line as a function of intensity. This system ultimately allowed measurements of the space charge tune shift which could be used for step-wise compensation [4] during stacking. The measurement system was destructive to the beam (emittance) and never became robust enough to be used operationally.Figure 2 from [4] shows the procedure for space charge compensation while stacking. The working line was "pre-stressed" for currents of 3 amperes and after the 3 amp increment of current had been stacked the next pre-stress was applied. Figure 2 shows the pre-stresses up to a total of 15 amps. This space charge compensation system took advantage of the great magnetic flexibility allowed by the combined function magnets and the inclusion of 24 pole face windings. The method also greatly stressed the capabilities of the controls system of the early seventies.

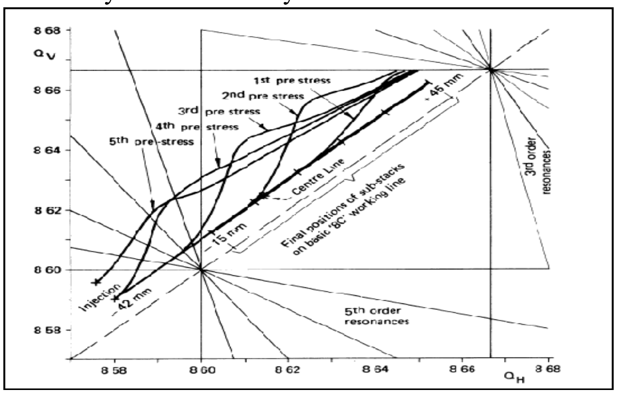


Figure 2: Working line and space charge compensation.

Schottky Scans

Schottky scans resulted from the discrete nature of the particles in the beam. A sensitive high frequency longitudinal pick-up with some long term averaging of the signal could show a signal proportional to the longitudinal phase space density of the debunched beam. Figure 3 shows one of the first Schottky scans taken operationally in the ISR. The three scans were taken at beam currents of 10, 15 and 19.2Amperes. The horizontal axis is the longitidunal frequency and allows evaluation of the beam $\Delta p/p$.

Soon after discovering longitudinal Schottky scans, transverse pick ups were used to measure the transverse Schottky scans which gave some information about the tune values in the stacked beams.

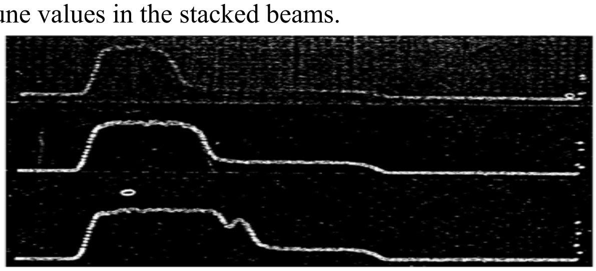


Figure 3: Longitudinal Schottky scans.

The operational use of these Schottky scans completely transformed the way of operating the ISR. On the long stable beams fills, they were the only diagnostic available for observing the beam in a quantitative way (there was also a very useful sodium curtain which allowed visual inspection of the cross-section of the beam). In the longitudinal plane the longitudinal density could be evaluated as a function of $\Delta p/p$ by incorporation the value from the current meter. In addition, any "markers" on the stacks which could be identified in all planes would allow an evaluation of the location of this marker in tune space. The most usual markers for some time were the edges of the stack.

Inserting Markers in the Stack

As previously explained, complete traversal of the stack by empty RF buckets causes a change in the average momentum of the whole beam. It is then clear that partial traversal will change the momentum of that part of the stack that has been traversed. This was a simple procedure, the RF was programmed to go from low momentum (outside the stack) to a momentum inside the stack, In this case a small reduction in the average momentum of the traversed part of the stack occurred, leaving a "marker" (lower density) at the $\Delta p/p$ where the RF traversing bucket stopped [5].

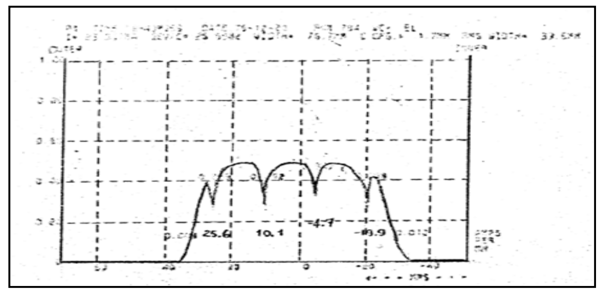


Figure 4: Longitudinal Schottky with markers inserted by phase displacement.

Figure 4 shows a longitudinal Schottky which had 4 markers inserted in this way. The markers are very clear and correspond precisely to the programmed frequency of the RF stop. Of course to be of any diagnostic use these markers must also be seen in the transverse plane.

Figure 5 shows the corresponding scans for the horizontal and vertical planes. The markers are clearly visible.

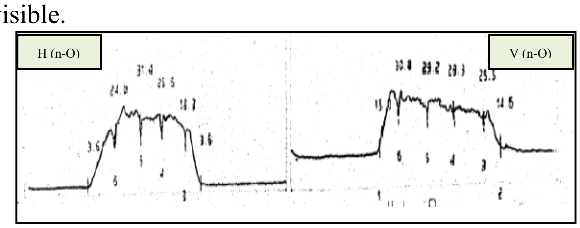
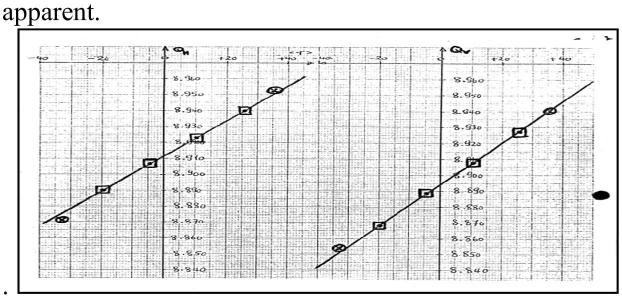


Figure 5: Transverse Schottky with same markers apparent.



.

Figure 6: Resulting measurement of the working line.

The combination of these measurements allowed plotting of the working line (see Figure 6 for this particular case) in a non-destructive way and the markers lasted throughout the physics runs.

Working Close to the Integer

In the early days (lower intensity, hence lower chromaticity) the working line was situated just above the half integer (8.5). In the latter, higher intensity days, when more tune spread was needed, we were forced to operate just below the integer resonance (9.0) since this is the most resonance free area on the tune diagram. The "top" of the stack was situated at a horizontal tune value of 8.955, just .045 distant from the integer. Initial operation at these new tune values was very problematic (orbit stability, transverse stability etc,) but with time all these known problems were solved. However there was an effect unknown at the time, which caused massive emittance increase in the top portion of the stacks. The sodium curtain showed transverse cross-sections of the beams which resembled lacrosse sticks.

Overlap Knock-Out

In the ISR we had to worry about 4 beams: 2 beams per ring. The bunched beam at injection and during acceleration and the debunched already accumulated beam.

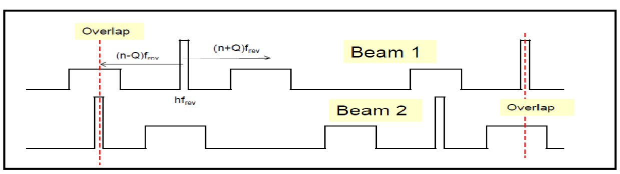


Figure 7: Transverse frequency overlap.

For beams that have significantly different revolution frequencies (caused by different Δp/p or different charge/mass ratios), overlap knock out was discovered to be an effect where the longitudinal harmonics of the bunch spectrum have components which are equal ("overlap") to the transverse betatron frequencies and thereby, by some form of coupling, can excite the beam at its transverse resonant frequency ("RF knock-out") as shown in Figure7.

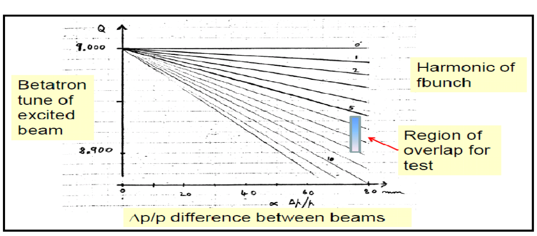


Figure 8: The OLKO resonance conditions for the ISR.

The OLKO resonance condition [6], Q vs Δp/p can easily be evaluated and is depicted in Figure 8 for the various harmonics of the bunch frequency. Clearly this condition is much more easily met at lower harmonics of the bunch frequency when the transverse tunes approach the integer.

An experiment was performed to test the strength of these new resonances. A beam of 8 Amperes was accumulated over the tune space shown in Figure 8 and collimated by scrapers so that any emittance increase would be recorded as beam losses. A bunched beam of 80mA was injected in the other ring and allowed to circulate for 360 seconds. Figure 9 shows the longitudinal Schottky scans before and after the 360s presence of the injected beam. The total current was reduced from 8 to 3A, the peak longitudinal density reduced from 0.5 to 0.26 A/mm and the whole top part of the stack had been eroded. The beam-beam tune shift exercised by the 80mA bunched beam was of the order of 10^{-6}!

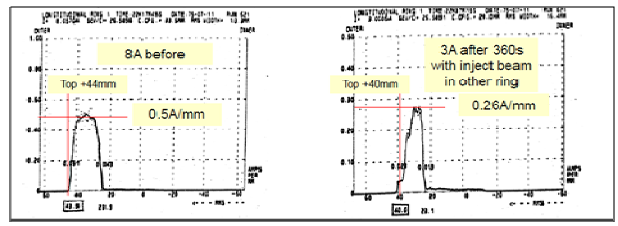


Figure 9: Density profiles before and after OLKO.

The OLKO effect was studied extensively in the ISR and cures were found to allow operation very close to the integer. The cures used operationally [6] were:

- Reduction of the higher harmonics of the bunch spectrum by bunch lengthening (lower RF voltage),
- Use of separations in the interaction regions so that the vector sum of beam beam kicks over one turn is minimized.

In order to complete the study, tests were also done with bunched colliding beams [7] with future accelerators in mind. In general, with bunched beams the resonance condition is not met if the RF frequencies of both beams are locked. For cases where frequency locking is not possible (e.g. resulting orbit is outside the vacuum chamber!) OLKO can be very destructive. This is particularly true for beams of different species and may cause operational difficulties for LHC colliding protons with lead ions.

Stochastic Cooling

The first observations of the stochastic signals in the ISR (Schotty scans) immediately turned attention to the possibility of damping the oscillations of the particles (Stochastic Cooling). Significant effort in this direction was led by Wolfgang Schnell following the initial idea by Simon Van Der Meer. A stochastic cooling test system was built as a demonstrator. The most sensitive detection of transverse beam size in the ISR was through the normalised luminosity measurement.

Figure 10 shows the results of the first conclusive observation of stochastic cooling.

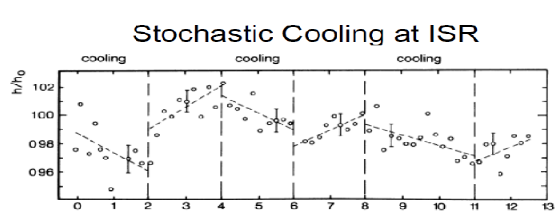


Figure 10: First observation of stochastic cooling

The normalized luminosity is shown over a 13 hour period with stochastic cooling turned on and off every few hours. The effect is small but very significant: stochastic cooling worked! Very soon afterwards a similar system was designed for the Initial Cooling Experiment (ICE) with spectacular results as shown in Figure 11.

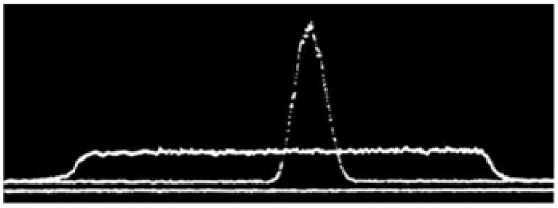


Figure 11: Fast momentum cooling in ICE.

LEP

LEP produced its first collisions on August 13th 1989, less than six years after ground was broken on September 13th 1983. The 27km tunnel extends from the foothills of the Jura mountain to the Geneva airport and straddles the border between France and Switzerland. The 3.8 m diameter machine tunnel is buried at a depth varying between 50 and 175 m.

The Large Electron Positron collider LEP at CERN was commissioned in 1989 and finished operation in November 2000. During this period it was operated in different modes, with different optics, at different energies, and with varied performance [8], [9]. In the end, LEP surpassed all design parameters. It has provided a large amount of data for the precision study of the standard model, first on the Z^0 resonance, and then above the W pair threshold. Finally, with beam energies above 100 GeV, a tantalizing glimpse of what might have been the Higgs boson was observed.

LEP Performance

Performance at LEP naturally divides into two regimes: 45.6 GeV running around the Z^0 boson resonance and high energy running above the threshold for W pair production. A summary of the performance through the years is shown in Table 1.

In the regime on or around the Z^0 resonance, performance was constrained by the beam-beam effect which limited the bunch currents that could be collided. The beam-beam effect blew up beam sizes and the beam-beam tune shift saturated at around 0.04. Optimization of the transverse beam sizes was limited by beam-beam driven effects such as flip-flop. The main breakthrough in performance at this energy was an increase in the number of bunches: First with the Pretzel scheme (8 bunches per beam) commissioned in 1992, and then with the bunch train scheme (up to 12 bunches per beam) used in 1995. The optics (phase advance and tunes values) were also changed in attempts to optimize the emittance and the beam-beam behaviour.

With the increase in energy to above the W pair threshold the beam-beam limit increased and the challenge was to develop a low emittance optics with sufficient dynamic aperture to go to the 100 GeV regime. Luminosity production was maximized by increasing the bunch current to the limit while operating with four bunches per beam and rigorous optimization of vertical and horizontal beam sizes.

Table 1: Overview of LEP Performance from 1989 to 2000

Overview of LEP performance from 1989 to 2000. $\int \mathcal{L}dt$ is the luminosity integrated per experiment over each year and I_{tot} is the total beam current $2k_bI_b$. The luminosity $\mathcal{L}$ is given in units of $10^{30}\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.

Year	$\int \mathcal{L}dt$ (pb^{-1})	E_b ($\mathrm{GeV/c^2}$)	k_b	I_{tot} (mA)	$\mathcal{L}$
1989	1.74	45.6	4	2.6	4.3
1990	8.6	45.6	4	3.6	7
1991	18.9	45.6	4	3.7	10
1992	28.6	45.6	4/8	5.0	11.5
1993	40.0	45.6	8	5.5	19
1994	64.5	45.6	8	5.5	23.1
1995	46.1	45.6	8/12	8.4	34.1
1996	24.7	80.5 - 86	4	4.2	35.6
1997	73.4	90 - 92	4	5.2	47.0
1998	199.7	94.5	4	6.1	100
1999	253	98 - 101	4	6.2	100
2000	233.4	102 - 104	4	5.2	60

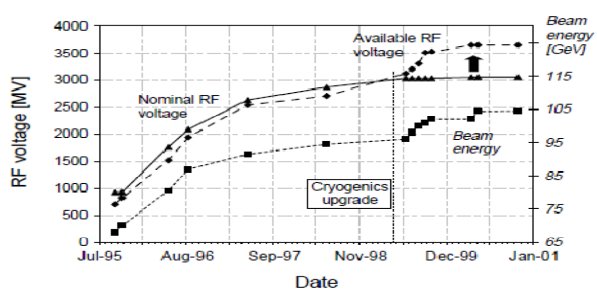


Figure 12: RF voltage per turn over the years.

Between 1996 and 2000 the beam energy was progressively increased from 80.5 to 103 GeV. At these energies beam oscillations are strongly damped and the single particle motion has an important random walk component due to the large number of emitted photons. Consequently particles no longer lock on resonances driven by the non-linear beam-beam force and beam size blow up is reduced allowing the use of higher bunch currents. Record beam-beam tune shifts of above 0.08 were achieved in each of the 4 collision points. In order to reach these very high energies the superconducting cavities were all driven beyond their design values to reach a total accelerating voltage per turn of more than 3.6GV. (see Figure 12 for the progression in accelerating voltage).

The design and achieved values for a number of crucial LEP performance parameters are summarized in Table 2.

It is seen that LEP clearly surpassed all design expectations. In particular the peak luminosity at LEP2 was almost a factor of 4 above design.

Table 2 : LEP Performance Parameters

Parameter	Design (55 / 95 GeV)	Achieved (46 / 98 GeV)	
Bunch current	0.75 mA	1.00 mA	
Total beam current	6.0 mA	8.4 / 6.2 mA	
Vertical beam-beam parameter	0.03	0.045 / 0.083	
Emittance ratio	4.0 %	0.4 %	× 10
Maximum luminosity	16 / 27 10^{30} cm^{-2}s^{-1}	23 / 100 10^{30} cm^{-2}s^{-1}	× 1.4 / 3.7
IP beta function b_x	1.75 m	1.25 m	
IP beta function b_y	7.0 cm	4.0 cm	

LHC

The status of the commissioning of the LHC has already been reported at this conference [10]. However during the 3 days between the LHC status presentation and this presentation, the LHC machine has increased the number of bunches in physics from 6 to 13 and more than doubled the peak luminosity for data taking (see Figure. 14).

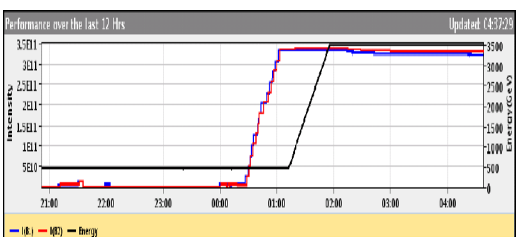


Figure 14: Intensity (red/blue traces) and energy in the LHC.

LHC in The next decades

Luminosity Upgrade

The present goals for the LHC, as set by the experimenters are for an integrated luminosity (with protons) of around 1fb^{-1} by the end of 2011. In addition there will be 2 periods of operation with colliding lead ions, each for about one month. The ion running periods are foreseen towards the end of 2010 and 2011.

In 2012 LHC will be stopped for a long shutdown of duration of about one year in order to complete the consolidation of the inter-magnet connectors. Several other consolidation programmes are foreseen during this shutdown both for the LHC and the injectors. Following this shutdown the goal is to operate close to 7TeV per beam with high intensity beams. Operation at 7TeV per beam is foreseen to continue until at least 2030 with a major luminosity upgrade around 2020-2021. The performance aims of this upgrade is ~5x10^{34}cm^{-2}s^{-1} with a long luminosity lifetime provided by "levelling". Luminosity levelling may be provided by optimization of the collision region parameters as a function of the decaying beam current during the course of the physics fill. To accomplish this, it is foreseen to vary the β*, the crossing angle and the bunch length. In addition, R&D has started with an aim to provide very low β values at the interaction point by the possible use of new superconducting Nb_3Sn, as well as studying the design and construction of crab cavities.

The present idea is that this upgrade in luminosity will be synchronized with upgrades of the LHC detectors.

Energy Upgrade

Preliminary work has recently started to investigate the long term possibilities of a substantial energy upgrade of the LHC. A first set of parameters has been produced which looks very interesting.

The optimization of luminosity in the parameter space of such a high energy collider must use a new approach since in this energy range, synchrotron excitation and damping become significant. For example at 16.5TeV per beam the longitudinal damping time is of the order of one hour and the equilibrium transverse emittance would become vanishingly small were it not for other effects life intra beam scattering. For such a machine, luminosity levelling will almost certainly come for free due, to this synchrotron damping. However the damping is possibly not fast enough to have a significant effect on the maximum permissible beam-beam strength parameter. It is not yet clear whether the beam-beam effect will produce an emittance blow up as in electron machines or (more likely) drive non-linear resonances which will produce high amplitude tails and beam losses as in lower energy proton colliders. We have launched work on large scale computer simulations, taking into account all known effects in order to answer some of the previous questions.

It is clear that such an upgrade is not for the immediate future but a reasonable aim is to be ready by the end of the life of the present LHC sometime in 2030.

REFERENCES

[1] M.Jacob, K. Johnsen; CERN84-13 (Nov 1984)

[2] K.Hubner; CERN-AB-2005 (June 2005)

[3] "Longitudinal Behaviour of the Stacked Beam and the RF Parameters During Phase Displacement to 31.4 Gev/c", CERN ISR-OP/76-44, October 1976

[4] P.J. Bryant et al. CERN-ISR/75-54

[5] S. Myers ISR Performance report 11th January 1977

[6]; "Overlap Knockout Resonances in the ISR", IEEE Trans. on Nucl. Sci. NS-24, No 3 (p1405), June 1977

[7] "Overlap Knockout Resonances with Colliding Bunched Beams in the CERN ISR", IEEE Trans. on Nucl. Sci. NS-26 No.3 (3574), June 1979

[8] "Accelerator Physics at LEP". In Reports on Physics in Progress, Vol 63, Number 6, (2000), pp939-1000, published by IOP. Also CERN SL-2000-0037-DI, July 2000

[9] "A Brief History of the LEP Collider". Nuclear Physics 9 (Proc. Suppl.) 109B, pp. 17-31 (2002), also CERN-SL-2002-009

[10] S.Myers;"LHC Commissioning and First Operation". IPAC'10, May 2010, Kyoto