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LABORATOIRE DE L'ACCELERATEUR LINEAIRE**

CERN-LEP/TH/83-15/Rev.
CERN/PS/DL/83-23
CERN/SPS/83-22
LAL/RT/83-08

THE CHAIN OF LEP INJECTORS

LEP Injector Study Group

Presented at the 1983 Particle Accelerator Conference,
21-23 March 1983, Santa Fe, New Mexico

*Geneva, Switzerland
**Orsay, France
March 1983

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Summary

The CERN 400 GeV Proton synchrotron (SPS) will be used as 20 GeV positron/electron injector of the Large Electron-Positron storage ring (LEP) under construction at CERN. The SPS will be fed with 3.5 GeV positrons/ electrons from the CERN 28 GeV Proton Synchrotron (PS) which in turn receives the particles from a new pre-injector under construction. The latter consists of a 600 MeV storage ring acting as a buffer between a 600 MeV S-band linac cycling at 100 Hz and the slow-cycling synchrotrons; the positron source is a converter target downstream of a 200 MeV linac.

1. Introduction

The injection system has to provide e^+ and e^- beams at intervals of between two to four hours, depending on the operating conditions of LEP². Simultaneous accumulation for e^+ and e^- with a rate of 0.25 mA/min per LEP beam consisting of four bunches is aimed at, which implies a filling time of 12 min for the nominal LEP current of 3 mA per beam.

Originally, it had been planned to build a new, dedicated 22 GeV synchrotron in a tunnel touching the arc of LEP³. However, the proximity of LEP to the SPS, chosen in view of possible ep collisions between LEP and an SPS bypass, prompted the proposal⁴ to use the SPS/PS complex as 20 GeV e^+/e^- injector in order to minimize costs. Although the synchrotrons will need some extra equipment to make them suitable for the acceleration of these light particles, the only substantial additions required are the 600 MeV pre-injector for the PS and the 20 GeV beam transfer lines from SPS to LEP.

The SPS has a dead-time in between the 450 GeV proton acceleration cycles which is imposed by the limit on the mean power dissipation in the magnets. Since the e^+ and e^- are accelerated in this dead-time, the LEP filling does not interfere with the proton programme of the SPS. However, the filling of LEP and the use of the SPS as proton-antiproton collider are not compatible but appropriate scheduling can take care of this problem.

After a general description of the injector chain, this paper describes the planned mode of operation and the individual subsystems. It concludes with a short status report. More details can be found in a forthcoming design report.

2. General Description

Fig.1 shows a schematic diagram of the LEP injector chain. The pre-injector consists of the LEP Injector Linacs (LIL) and the Electron/Positron Accumulation ring (EPA). The intense e^- beam (2.5 A peak) of the 200 MeV e^- linac (LIL1) produces the e^+ in the converter target upstream of the 600 MeV low-intensity linac (LIL2). The e^- for the e^- filling of LEP are produced by a low-intensity gun located near the converter.

The two linacs together are in total approximately 100 m long and their position is about radial to the PS with the second linac extending under the EPA ring in order to save on total length (LIL-EPA orbit separation 15 cm). The circumference of EPA is grossly determined by the requirement that its kicker magnets should independently handle each of the 8

Fig.1 Schematic layout of LEP injector chain. Existing parts thick line; possible SPS by-pass for LEP ep option dashed line. Only the part around crossing point 1, of LEP, is shown.

bunches. Since injection with a rising field in the PS is preferred, which necessitates beam transfer within one PS turn, the EPA circumference (125.7m) is chosen to be exactly one fifth of the PS. EPA has its long axis on the linac axis and it is sited close to the PS to which it is connected by two new, short transfer lines. The race-track shape chosen for EPA (49m x 21m) makes best use of the available space.

Since the PS has a combined-function lattice a Robinson wiggler⁵ is needed to modify and control the damping partition⁶. The wiggler together with the additional RF-system for acceleration needs straight-section space which is very scarce in this multi-purpose machine. For this reason, it cannot be envisaged to accelerate the particles much above 3.5 GeV in the PS, at least not in the initial phase. Since the emittances are smaller than the proton emittances, the particles can be accepted by the SPS at this relatively low energy. However, in order to prevent single-bunch instabilities and avoid beam loss, the total charge to be accelerated per pulse must be distributed over many bunches. This is the reason for using 8 bunches in all the circular injector machines.

The e^+ are sent to the SPS via the existing proton beam line TT10 and the e^- through the antiproton beam line TT70. The particles are accelerated to 20 GeV in the SPS by an additional 200 MHz RF-system

* The study and construction of the LEP pre-injector linacs is being made in a collaboration between CERN and LAL¹.

consisting of 32 cavities and, after ejection from the long straight section LSS6 of the SPS, they are sent to LEP through two new transfer channels. Finally, the beam is injected in the arcs of LEP about 560 m away from the LEP crossing point 1.

3. Description of operation

Four e-acceleration cycles are fitted in the deadtime of the SPS between the proton cycles. Fig.2 gives schematically the magnet supercycle of SPS and PS, the total beam current in EPA and the pulsing periods of the linac versus time. The first two e-cycles are used for e^+ acceleration, the last two for the e^- . Hence, both beams in LEP are built up nearly simultaneously so that RF beam loading and space charge detuning are the same for both beams, and correction of these effects is facilitated.

Fig.2 Schematic diagram of SPS and PS magnet cycle, EPA total beam current and linac pulsing periods (peak current) versus time. Number of bunches and sign of charge indicated on cycles.

One period corresponding to a SPS supercycle in the middle of a LEP filling is examined in the following. Fig.2 shows that the e^+ are collected in EPA during the relatively long SPS proton cycle because the linac e^+ current is low. The linac pulses are put in turn into the eight buckets of EPA by stacking the pulse in betatron phase space close to the stored bunch. The time elapsing between two injections into the same bucket is 80 ms, sufficiently long compared to the EPA damping time ($\tau_x=30$ ms).

Once the required intensity is reached each of the 8 e^+ bunches is moved onto a thin electrostatic septum which cuts the bunch into two halves and deflects one half into the transfer channel to the PS. The other 8 halves remain in EPA and are saved for the next e^+ cycle. The 8 bunches injected into the PS are accelerated to 3.5 GeV and transferred to the SPS where they are accelerated to 20 GeV and sent to LEP. In LEP, two SPS bunches are stacked, either in horizontal betatron or synchrotron phase space, close to each one of the four circulating bunches so that, after injection, each stored LEP bunch has two companions performing damped betatron or synchrotron oscillations around it ($\tau_{xLEP}=0.4$ s, wigglers on).

The second e^+ cycle starts with the transfer of the remaining 8 half bunches from EPA to the PS, and this second e^+ batch is handled in the same way as the first batch in the rest of the injector chain.

As soon as the e^+ are ejected from EPA the linac starts to inject e^- . The eight complete e^- bunches are then transferred through the two synchrotrons to LEP in the same way as the e^+ . After the second e^- cycle, identical to the first one, the linac resumes

e^+ injection into EPA.

Table 1 gives some key parameters, the linac intensity, and the bunch intensities. The last column shows the transfer efficiencies.

Table 1, Nominal parameters

e-cycles/supercycle	4		
Supercycle period (s)	15.12		
Particles	e^+	e^-	
Linac peak current (mA)	8.0	40	
pulse length (ns)	12	12	
rep.frequency (Hz)	100	100	
part.per pulse/ 10^{10}	0.060	0.30	
Accum.time EPA (s)	11.22	1.14	30%
EPA 0.6 GeV Nb/ 10^{10}	2.5	1.3	80%
PS 0.6 GeV Nb/ 10^{10}	1.0	1.0	80%
SPS 3.5 GeV Nb/ 10^{10}	0.81	0.81	90%
at LEP septum Nb/ 10^{10}	0.73	0.73	30%
in LEP trapped Nb/ 10^{10}	0.22	0.22	
LEP accum.rate (mA/min)	0.25	0.25	

4. Description of individual systems

4.1 Pre-Injector

The main parameters of the pre-injector are determined by e^+ operation. The mean resolved e^+ current produced by the linac is fixed by the required LEP accumulation rate and the transfer efficiency between LIL and LEP. Given the charge per pulse accelerated in LIL1 as well as the dipole field and kicker risetime in EPA, the two LIL energies and the LIL repetition frequency can be roughly determined from a cost optimisation. In order to keep the linac energies and therefore cost to a minimum, the pulse charge in LIL1 is chosen as high as possible limited only by the admissible energy spread due to beam loading which, if excessive, would preclude focusing of the beam to a small spot at the converter. The required linac energies are also reduced if the repetition rate is high. Since this rate is governed by the damping rate of EPA, a high dipole field is chosen in EPA for enhancing synchrotron radiation and the kicker rise/fall time is made very short (40ns) to minimize the revolution time, which leads to a short damping time.

LIL The front-end of LIL1 consists of a 90 keV triode gun delivering 6 A, a prebuncher cavity and a 30 MeV standing-wave (SW) buncher. The beam pulse length can be adjusted between 8 and 25 ns. The buncher is followed by 4 travelling-wave (TW) accelerating sections. The 6m long region between the two linacs contains the triplet for e^- focusing and the converter target; the 60 keV off-axis low-current e^- gun and the on-axis e^- prebuncher plus a 4 MeV SW buncher. LIL2 consists of 12 TW sections of nearly identical design as the LIL1 sections with solenoid focusing on the first two sections followed by a FODO system.

The 3 GHz power sources are 35 MW klystron amplifiers; each of them powers 4 sections using the LEP Injector Power Saver configuration (LIPS) which is based on the SLAC SLED scheme⁷. The acceleration rate in the first two sections of LIL2 is low (7 MeV/m) because of a possible reduction in breakdown strength in the high radiation environment just after the converter. These two sections and the last two sections are powered from two klystrons without LIPS.

The accelerating sections are disc-loaded waveguides working in the $2\pi/3$ TW mode with quasi-constant field gradient. The section length of 4.5 m results from a compromise between the number of klystron stations and the technical difficulties with

longer structures. The basic performance calculated for the chosen design is an energy gain of 60 MeV for 15 MW input power of which 12 MW is dissipated in the section. The section is constructed from 135 elementary cells. To reduce the number of different cell types required, the section consists of 9 constant impedance parts where the cells are identical.

EPA In order to enhance the horizontal damping during injection, the FDDF type lattice⁸ has a horizontal damping partition number of $J_x=2$. The concomitant low value of $J_e=1$ yields a large equilibrium energy spread as needed for beam stability. This repartition of damping is obtained by a magnetic field gradient of -1.0 T/m in the sixteen 0.56 m long bending magnets. A relatively high dipole field (1.4T) for these short magnets is adopted to enhance radiation damping and the equilibrium energy spread in the beam.

A radio-frequency of 19.1 MHz corresponding to the lowest possible harmonic number 8 is chosen so that the RF voltage is minimized. A peak voltage of 50 KV is then sufficient to replace the radiation loss of 8 KeV per turn and to produce the required RF bucket height for the accumulation of the linac e^+ pulses having large relative energy spread ($\pm 1\%$). The linac pulse length fits easily into the RF bucket leaving some latitude for trading peak current/pulse length against the energy spread due to the phase spread in the linac beam.

4.2 Modifications and additions to the synchrotrons

Relatively few modifications are required because e-operation is very similar to proton operation and the beam transfer of e^+ and e^- between the two machines uses the same equipment as the $p\bar{p}$ transfer. The synchrotron radiation power is very weak due to the low beam currents and the radiation does not penetrate the vacuum chamber walls except at the highest energies of the SPS. Since the resulting radiation dose per year remains small compared to the dose received during proton operation, this is of no concern. Initial radiation-induced outgassing is expected to be high but dedicated beam-cleaning runs will reduce the pressure rise to an acceptable level. In the PS, some improvements of the more contaminated parts of the vacuum system might be required. The new RF cavities must be strongly damped during proton operation to avoid instabilities. An important effort will be needed to deal with the increased complexity of the operation.

Since the PS has a combined-function lattice, the horizontal betatron oscillations are anti-damped ($J_x = -1$) and the equilibrium energy spread ($J_e=4$) at 3.5 GeV is very small. Although the effect of the anti-damping could be limited by operating with a short accelerating cycle, the energy spread determined by adiabatic damping and the small equilibrium value turns out to be unacceptable for beam stability at this low injection energy of the SPS. It is proposed to install 2 Robinson wigglers, so that the damping partition numbers can be changed at will⁶, and to add a 114 MHz RF cavity (1MW) producing the correct bunch length and replacing the radiation loss of 0.2 MeV per turn. With this equipment two different modes of acceleration up to 3.5 GeV are possible.

The largest addition to the synchrotrons is the RF-system in the SPS consisting of 32 (200 MHz) cavities providing together a peak voltage of 32 MV. The present 200 MHz RF-system consists of TW structures which provide only 8 MV but cope with the large frequency swing and heavy beam loading occurring

during proton operation. Its extension is not practical because the effective energy gain per unit length is relatively low. The new cavities will be installed in the two missing-magnet straight sections on either side of long straight section LSS3 which houses the TW system. Each cavity has its own 65 kW tetrode amplifier sitting on top of the cavity and coupled directly to it.

4.3 Beam transfer from SPS to LEP

Positrons and electrons are ejected from the SPS in straight section LSS6 partly using equipment of the proton ejection (see Fig.1). The transfer tunnels lead from LSS6 downwards to LEP with slopes reaching 16% in order to make the transfer tunnels as short as possible. After having passed a phase-plane exchange section the injected beam approaches LEP from above and is bent into the plane of the LEP ring by a steel-septum magnet. The beam now continuing just outside the LEP aperture then enters a copper-septum magnet which makes it parallel to the already circulating beam. The latter is brought close to the other side of the 2mm thin septum by a fast orbit bump. In order to be able to generate a bump independent of the LEP phase advance three kicker magnets are foreseen. Space for the injection equipment is created in the lattice by reducing the number of dipole magnets in the 2x2 injection cells. Consequently, the magnetic field of the remaining dipoles must be increased so that the LEP geometry is conserved. Judicious choice of the longitudinal position of these dipoles also avoids perturbation of the dispersion function in the rest of LEP.

5. Status

Most of the equipment is under design and prototype work is advancing. The gun-buncher ensemble of the high-intensity linac has already operated according to specification in a test delivering currents up to 10 A within 10 ns pulse length at 25 MeV. The linac TW section is designed and a 1.5 m long prototype is built. Prototypes of the 35 MW klystrons are under development in industry and a prototype klystron modulator is near completion. The LIPS system has been tested using a resistive load; the expected power enhancement with an instantaneous peak power of 100 MW has been obtained using a 20 MW klystron¹⁰. The area near the PS foreseen for the pre-injector has been cleared and the linac building is under construction. A prototype wiggler for the PS will be available this year for the first tests with proton beams to verify effects on the optics of the PS. The new SPS cavities are in fabrication and measurements of damping behaviour and higher-order mode excitation have been performed with proton beams on a passive prototype cavity in the SPS ring. Tests of the prototype tetrodes are under way and the required power level of 65 kW has been reached during operation with a resistive load.

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