ENERGY RAMPING IN LEP

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Abstract

The technique developed for energy ramping of the beams in the LEP collider allows for the easy generation of intermediate energy files since the dynamic corrections necessary during the ramp are managed by the distributed equipment controllers. In this way, optics parameters can be computed independently of the ramp rate chosen for energy ramping

A report of the ramping technique is given with a description of the constraints imposed by beam dynamics and hardware considerations. Details are also given of the practical implementation of the system and the performance achieved so far.

Introduction

For the acceleration of the LEP beams from 20 GeV (E_{inj}) to the energy ($E_{flat\text{-}top}$) at which physics data taking is foreseen, machine parameters (e.g. optics functions, transverse and longitudinal tunes) obtained from theory, modelling computer codes and the known equipment characteristics, have to become actual parameters of the collider magnetic and RF accelerating systems.

An energy ramp requires the synchronization within 1 ms of the magnetic fields controlled by 172 power converters (PC's) for the lattice magnet circuits and of up to 568 PC's for the orbit and betatron coupling correction magnets, and of the accelerating cavities grouped (for the first phase of LEP) in 8 units of 16 cavities each.

Although energy and intensity dependent parameters are of course considered in simulation studies, the operational values are determined during acceleration on the collider itself, where all the imperfections of the models and of the hardware are encountered and can be corrected.

The procedures used in LEP are such as to

- provide the necessary synchronization of the magnetic fields and of the RF accelerating fields, in spite of the different static and dynamic characteristics of the various components;
- keep the modelling independent of actual acceleration parameters (e.g. ramping rate), in order to limit the quantity of reference data to be made available for day-to-day operation;
- incorporate in the distributed process and equipment controllers of the Radio Frequency and Power Converter systems the capability of adjusting basic data so as to take into account the actual parameters requested for acceleration;
- allow to control, monitor, record and, when possible, adjust during the ramp process , at stops or "on the fly", beam characteristics like tunes, chromaticity, closed orbits, betatron coupling;
- provide user friendly updating facilities for all the files containing the parameters governing a ramp, so as to easily incorporate in subsequent runs the necessary corrections.

Some basic principles of the ramp process

By means of the modelling programs, a number of collider states are defined between the injection and the final flat top energy, to describe the required changes of the machine optics and to correct for the energy dependent tune variations due to the imperfections of the main dipole bending field.

The energy spacing of the states is chosen so as to allow to interpolate linearly between them and so keep the occurring betatron tune changes (ΔQ's) to less than 0.01.

The states contain the whole set of optics data, the magnets' normalized strengths, the RF, beam and machine parameters defining the collider at a given energy.

From the states and the required acceleration rate, the set of values to be provided by the magnet PC's and RF as a function of time during ramping are then computed by ad-hoc programs running in the control system computers.

For the control of the magnetic fields, intermediate sub-states at intervals of 1.25 GeV or their multiple are calculated, so as to avoid non-linearities exceeding 10^{-4} in the field versus excitation current curves of the various magnets.

Intermediate sub-states can be generated at any time interval which is a multiple of 256 ms, corresponding to an energy interval of 0.125 GeV for the nominal ramp rate of 0.5 GeV/s; this feature has been very useful for the collider running-in.

By interpolating in tables obtained from the series magnetic measurements of all the LEP magnets, the normalized magnet strengths are then converted into actual excitation current values as function of time (and hence energy), and the corresponding current increments computed.

The latter increments are finally down-loaded to the equipment controllers of the individual power supplies, where they are further subdivided in so-called minivectors, so as to correspond to the basic time step of 256 ms or 0.125 GeV.

For the control of the accelerating fields in the RF cavities, the required total voltage at the different energy levels, as defined in the above mentioned states, is used to produce the voltage versus time tables to be then down-loaded to the data managers controlling each of the 8 RF units [1].

Alternatively, a constant synchrotron tune value can be also given as input for the computation of the RF tables to be used during the ramp.

The synchronization of the about 800 power converter and radio-frequency equipment controllers occurs via the General Machine Timing system (GMT) [2], which distributes all around the collider the trigger signals starting and stopping a ramp, and a 1 ms master clock signal for overall synchronization. The sequencing of timing events for equipment synchronization is shown in Fig. 1.

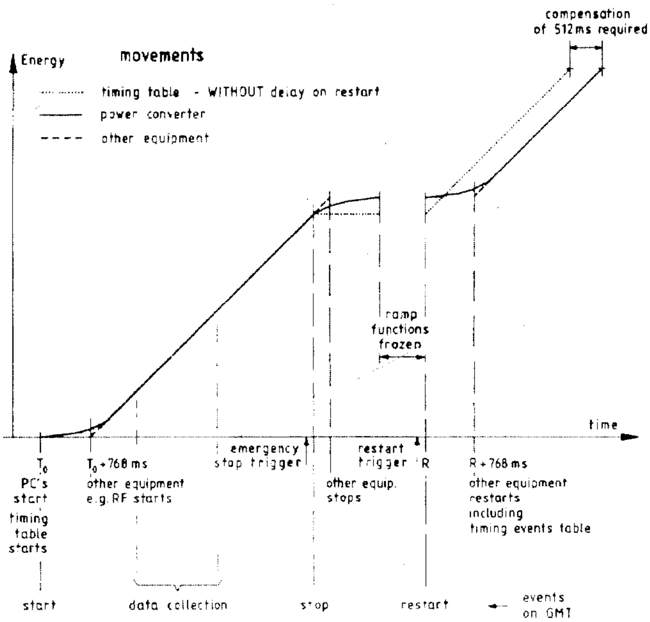

Fig. 1 - Timing events and equipment synchronization

Consideration of dynamic effects

The data preparation described above does not take into account dynamic effects, like delays and perturbations of the magnetic fields due to eddy currents in the vacuum chambers, the slow start and stop (Fig. 2) of the ramp in order to avoid delay-line effects in the long magnet chains and power converter control loop overshoots, and the different time constants of the various magnet circuits.

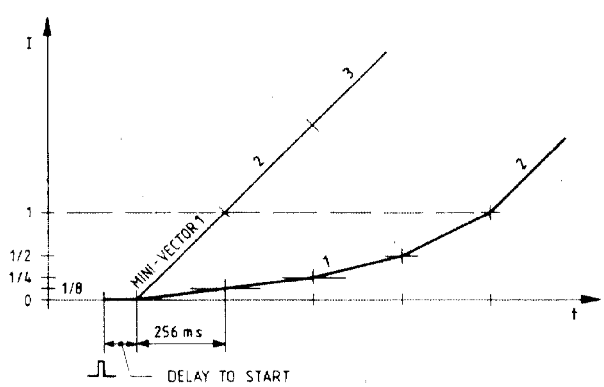

Fig. 2 - Slow start by stretching the first mini-vector from 256 to 1024 ms

The eddy currents set up in the vacuum chambers during ramping introduce a time lag between excitation current and the actual magnetic field inside the vacuum chamber, which is a characteristic of the system formed by a magnet and its vacuum chamber, independent of the ramping rate. Furthermore the eddy currents cause also local perturbations, directly proportional to the ramping rate, of the magnetic field distribution, causing tune and chromaticity shifts.

The above magnetic field time lag and quality perturbation have been measured and computed [3] for the LEP main dipole magnets, and then computed [4] also for the 15 remaining different magnet/vacuum chamber assemblies of the collider.

To synchronize the magnetic fluxes inside the dipole and quadrupole vacuum chambers in spite of the above time lag, balancing RC time constants (Fig. 3) have been incorporated between the DAC and the power converter control loop, to reduce the field mismatch.

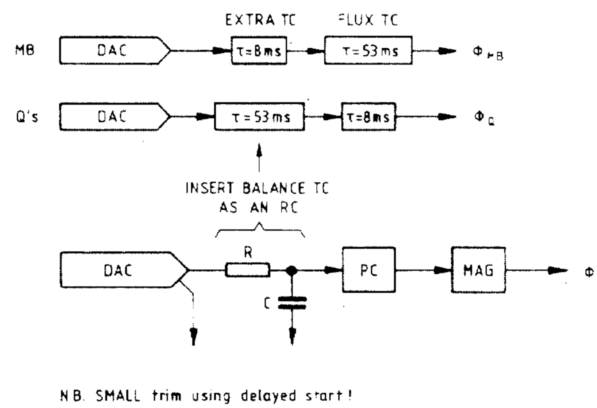

Fig. 3 - Balancing time-constants

Furthermore, the fine adjustment (± 150 ms) of the field versus time curves for each magnetic circuit can be achieved by delaying the start-up of the entire vector generation process in each power converter in steps of 1 ms. The delays established for each circuit are stored in tables which are downloaded to the PC controllers at the beginning of each ramp.

The eddy current induced local field perturbations in the main bending field, are mainly quadrupole and sextupole terms, which have to be compensated by the lattice quadrupole and sextupole magnets. As these perturbations depend on the ramping rate, a scheme has been implemented (Fig.4) by which the required compensating currents are added and subtracted in 4 steps, so as to follow the rounded off start and stop of a ramp, to the quadrupole and sextupole excitation currents.

The computed values of the above compensating currents have been used as a first approximation, experimental values for the quadrupole current have then been refined experimentally by monitoring the collider betatron tunes during ramping.

The nominal ramping rate can be divided by a factor 2^n (n = 1,4) without the calculation of new current increment tables. This allows the study of the various dynamic effects; all the dynamic corrections described above (rounded off start and stop, compensation of eddy current induced tune changes) are automatically adjusted accordingly in all the PC controllers, to which the ramping rate is downloaded as well.

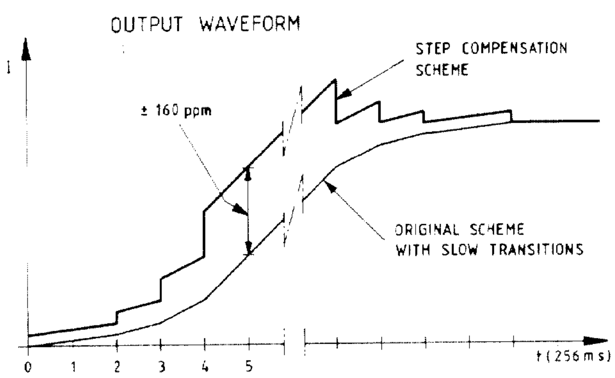

Fig. 4 - Compensation of the effects of the dipole vacuum chamber eddy currents by adding current offsets in the PC's of the quadrupole and sextupole circuits .

Diagnostic, beam instrumentation and corrections

The synchronization of the actual magnetic fields inside the dipole and quadrupole vacuum chambers can be monitored during a ramp by a field display system [5], where the actual flux is sampled inside reference magnets. This system was most useful in the setting-up and debugging of the PC's and timing system control software.

Beam current and life-time [6], beam size [7], betatron [8] and synchrotron tunes are monitored continuously during a ramp, allowing the detection of imperfections (e.g. crossing of resonances because of unwanted tune changes) or non-fatal faults (e.g. a RF trip), so that the ramp can be stopped by operator intervention to re-establish correct conditions.

A closed-loop control of the betatron tunes is being run in at the time of writing; this system has a range in tune of 0.05 x $E_{inj}/E_{flat\text{-}top}$ and updates the correcting currents in the PC's (within 200 ppm of Imax) of the arc quadrupole magnets at a frequency of 5 Hz, i.e at steps of 0.1 GeV for the nominal ramping rate.

This closed-loop control is designed to correct for the remaining field mismatches, the reproducibility errors and the short term drift of the PC's occurring in the daily operation.

The measurement and correction of the closed orbits, of the chromaticity and major tune variations, cannot be performed continously during a ramp; they are measured during machine development at intermediate energy levels and the corresponding corrections are introduced in the increment tables used by the PC's by means of an ad-hoc code, the ramp editor.

This code allows the application of incremental corrections either fixed or proportional to the beam energy, to the data in the tables for the magnet PC's; it has proven to be an essential tool for the efficient operation of the collider

Operational experience

It has been possible, without use of the tune feedback system, to keep the tune variation in the ramp smaller than 0.03 peak to peak, with the procedures described above; the synchrotron tune Q_S is kept at its present nominal value of 0.082 within ±0.001. A max current of 3.5 mA has been accelerated to 45.5 GeV (May, 1990) for physics with typical losses of 0.5 mA during ramping and the subsequent tuning of the vertical beta function at the interaction points from 21 to 7 cm. Better performance may be achieved when the tune feedback system comes into operation.

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