MULTICYCLING OF THE CERN-SPS: SUPERCYCLE GENERATION AND FIRST EXPERIENCE WITH THIS MODE OF OPERATION

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1. Introduction

The SPS was originally designed to accelerate protons up to 450 GeV and to eject the particles to fixed target experiments. Nowadays it also operates as a $p\bar{p}$ collider with constant or pulsing energy, as an ion synchrotron (O^{8}, S^{16}) and in the future it will serve as an electron/ positron injector for LEP.

The total operational time must be used in the most efficient way. By interleaving the lepton cycles between the cycles to accelerate protons or ions, the lepton acceleration can be achieved with very little perturbations to the fixed target physics program [1]. In addition, changing the mode of operation should be possible without substantial delays. The control system must allow "multicycling" as well as fast changes of the operational mode.

To fulfill these requirements the hardware of the control system was substantially upgraded : a new timing system and new function generators providing the reference functions for various types of equipment [2] replaced a major part of the old equipment, new console computers and a new computer network were added to the old control system.

The software for the SPS is based on an entirely new concept : all parameters describing the different cycles like reference functions for the magnets and the acceleration system, parameters for the timing system and various functions related to the beam physics (e.g. bunch length, chromaticity etc) are calculated offline in one step (SUPERCYCLE generation). When a SUPERCYCLE is initialized all necessary parameters for the equipment are send to the hardware [3]. Small changes (e.g. of the tune) can be done from the operator consoles based on data provided by the SUPERCYCLE generation.

2. Layout of a SUPERCYCLE

A SUPERCYCLE is a combination of different elementary cycles. An example is given in Fig.1: after the first elementary cycle to accelerate protons from 14 GeV to 450 GeV the magnets ramp down to the necessary field for lepton injection at 3.5 GeV. Positrons are accelerated in the first two lepton cycles while in the last one electrons are accelerated. Leptons can be accelerated up to 20 GeV in the first cycle and up to 14 GeV in the last two cycles.

An elementary cycle consists of several segments: beam-in segments with beam in the machine and beam-out segments to prepare the various accelerator components for the injection in the next elementary cycle (see Fig.2).

In the beam-in segments the beam is transferred from an initial state to a final state. For the lepton cycles the initial state is given by the beam parameters at injection (momentum, bunch length, emittances ..), the final state is given by the parameters at extraction (for LEP injection this will be an energy of 20 GeV and a bunch length of about 4 cm).

For the cycle to accelerate protons and antiprotons to prepare a physics run in collider mode, the initial state is given by the beam parameters at injection energy and by the machine optics with β functions at the interaction point of 3.5m * 7m. The final state is a coasting beam at 315 GeV with an optics with β functions of 0.5m * 1m at the interaction points.

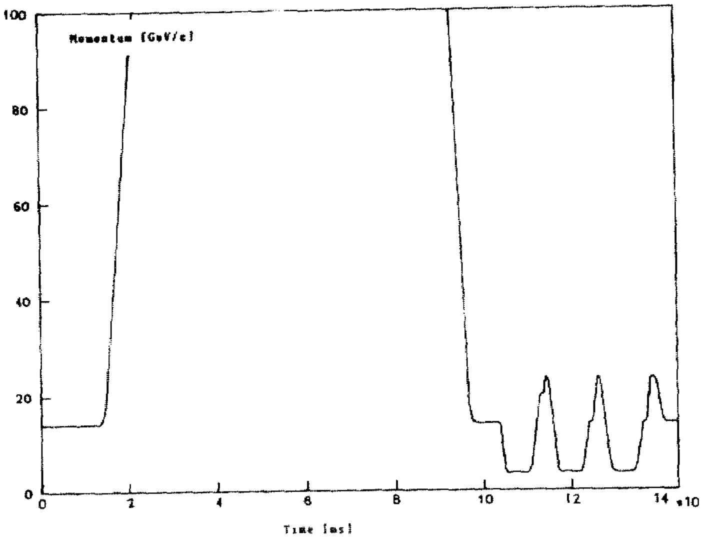

Fig.1: Layout of a Supercycle with one proton and three lepton cycles (only the part up to 100 GeV is shown)

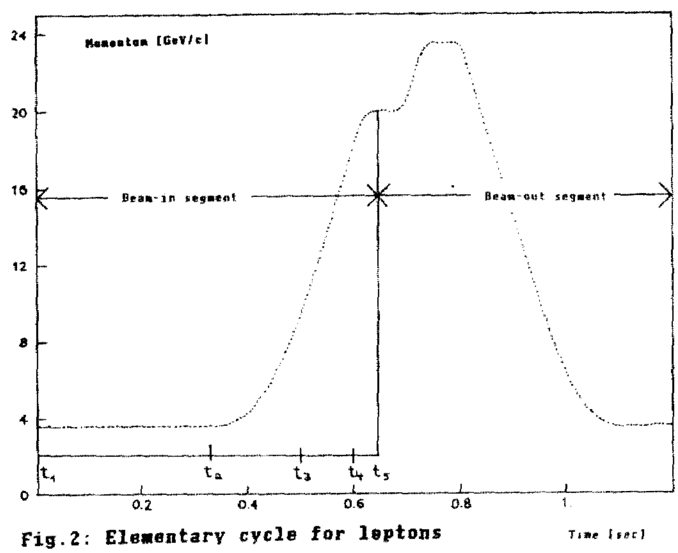

Fig.2: Elementary cycle for leptons

3. Construction of the segments

3.1 Calculation of the beam-in segments

As an example we describe the generation of a beam-in segment for an elementary lepton cycle. The energy for this cycle is shown in Fig.2 as a function of time. The leptons are accelerated from 3.5 GeV to 14 GeV. The bunches can be injected at any time between t_1 and t_2. The acceleration takes 265 ms. The extraction of the bunches towards LEP is done during the roundoff between t_4 and t_5.

Momentum and current in the main bending magnets: In the SPS the same power supplies are used for the proton cycles and for the lepton cycles. In the proton cycle the current goes up to a value of 6000 A corresponding to an energy of 450 GeV, in the lepton cycles the current is 38 A at injection. It is necessary to avoid fluctuations of the betatron tune larger than 0.02 and this requires the variations of currents to be smaller than 20 mA. The total dynamic range is in the order of 10^6. The required stability during the ramp could be achieved by raising the magnet currents very smoothly. The momentum is defined by the following functions :

$$p(t) = p_0 + a*t^3 + b*t^4 \qquad t = [t_2, t_3]$$

$$p(t) = p_1 + c*t \qquad t = [t_3, t_4]$$

$$p(t) = p_2 + d*t^3 \qquad t = [t_4, t_5]$$

The coefficients a,b,c and d are calculated assuming that p(t) is a twice continously differentiable function at $t=t_3$ and $t=t_4$. The magnetic field in the bending magnets is proportional to the momentum. The current is found in an array holding the current versus the magnetic field known from earlier measurements.

Another way of constructing a ramp is the calculation of the fastest possible ramp. The limitations can be given by any system in the SPS (current in the bending or quadrupoles magnets, acceleration voltage). The program will find the fastest ramp respecting all hardware limitations as described in [4].

Optics: For the calculation of the currents of quadrupoles and sextupoles the beam optics has to be specified. For lepton cycles only one optics is used. For the $p\bar{p}$ collider the β function at the interaction point is reduced from 7.0 m * 3.5 m to 1.0 m * 0.5 m after the particles have been accelerated to 315 GeV. This requires a dynamic change of the quadrupole and sextupole strengthes and different optics have to be used.

Quadrupoles: The quadrupole field gradient is given by $dB/dx=k*(B\varrho)$. The normalised quadrupole strength k is taken from the beam optics, the value for $B\varrho$ is known from the calculation of the momentum. The current for each value of the field gradient is again found in an array. The necessary information to allow small tune changes by the operator is provided in the following way: for each point along the ramp the change in current necessary to achieve a unit change of the tune is calculated, and this for all quadrupoles which are used to change the tunes.

Sextupoles: The calculation of the sextupole currents requires a knowledge of the chromaticity along the ramp. The model we have used is [5]:

$$\xi_h = a_h + b_h/p + c_h\,\dot{p}/p$$

$$\xi_v = a_v + b_v/p + c_v\,\dot{p}/p$$

where:

ξ.......chromaticity, $\xi = (\delta Q/Q)\ /\ (\delta p/p)$

a.......lattice chromaticity plus the chromaticity which is induced by sextupolar fields in the bending magnets. This is independent of the momentum.

b/p.....chromaticity induced by the remanent sextupolar field components in the bending magnets.

$c*\dot{p}/p$...chromaticity generated by eddy currents. In particular at low momentum this effect is substantial.

The subscripts v and h denote the vertical and horizontal plane.

For the lepton optics typical values for the coefficients are :

a = -1.00, b = - 3.4, c= .308 for the horizontal plane.
a = -1.42, b = + 9.5, c=-.280 for the vertical plane.

The chromaticity along the ramp is shown in Fig.3. The currents for the four sextupole families which are used to correct the chromaticity to a value around zero are then calculated using a matrix a_{ij} :

$$I_i = \sum_{i=1}^{4} \sum_{j=1}^{2} a_{ij} * \xi_{ij}$$

with I.... currents for the sextupoles
a.... matrix elements
ξ.... chromaticity to be corrected

The matrix elements are precalculated and read from the optics input. The sextupole currents to compensate the chromaticity in Fig.3 are shown in Fig.4. As for the tune, the current changes for the different sextupole families are given in order to change the chromaticity from the consoles by one unit.

Parameters related to the accelerating system: On the base of the momentum function the voltage for acceleration and some other useful parameters are calculated.

The input parameters for this calculation are the parameters of the injected bunches (as bunch length, energy spread, intensity) and the required parameters for the extraction.

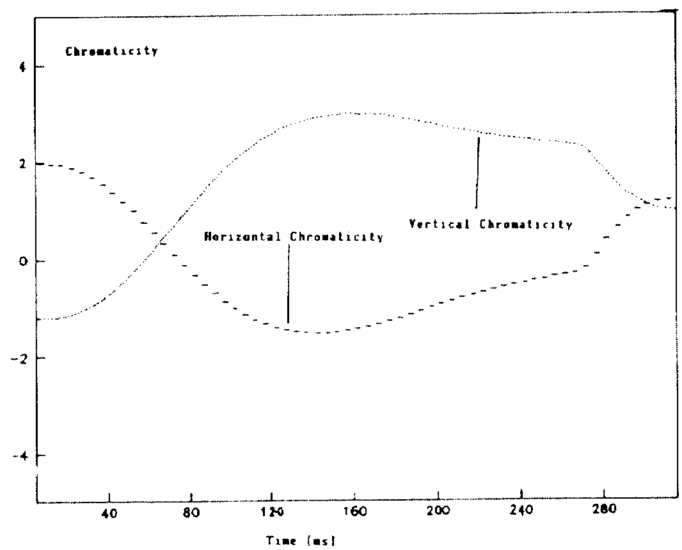

Fig.3: Applied chromaticity correction along the ramp

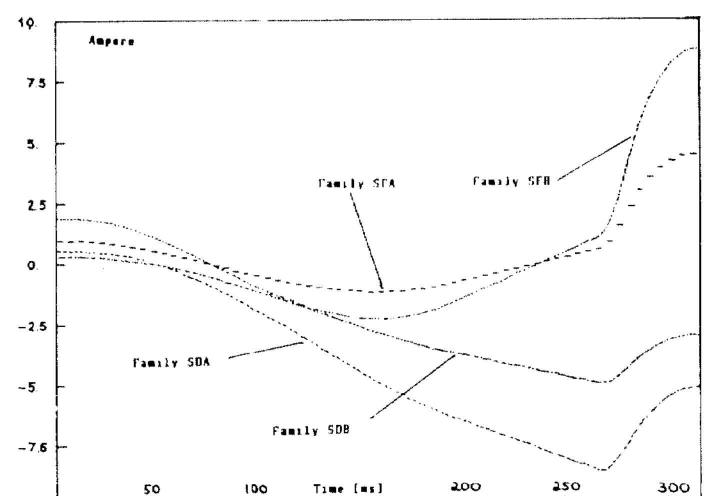

Fig.4: Sextupole currents in the different families to correct the chromaticity for a lepton cycle

The necessary voltage for capture and acceleration is then calculated (the synchrotron radiation losses and the required bucket area are included). Once the voltage is known, a set of beam parameters can be calculated : bunch length, energy spread, synchrotron frequency, instability thresholds etc. Some of these functions for the lepton ramp are shown in Fig.5. In the SPS the cavities are grouped in two families. The voltage on the beam is changed by changing both the voltage and the phase between the two cavity families, these functions are calculated in the SUPERCYCLE generation.

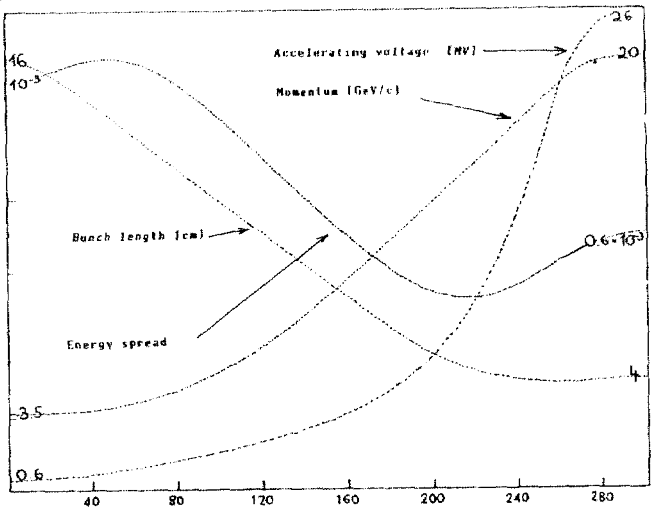

Fig.5: Accelerating voltage, bunch length and energy spread for a lepton cycle.

Output: All results of the calculation for the beam-in segment are written onto a file as a "MOPS" data structure [6]. All calculated beam-in segments are calculated and catalogued in order to be able to retrieve precalculated beam-in segments in an easy way.

3.2 Calculation of the beam-out segments

The beam-out segments are not explicitely computed but generated when the complete SUPERCYCLE is assembled.

4. The construction of the SUPERCYCLE

A SUPERCYCLE is a combination of different beam-in segments and the beam-out segments in between. First, the operator chooses from the catalog with all available beam-in segments the segments he wants to use for the SUPERCYCLE. Then the functions to connect two beam-in segments are calculated (e.g. the current in the main bending magnets down from the 450 GeV level to the injection level of the leptons).

In the SUPERCYCLE no time is available to demagnitise the various elements. This creates a history dependence of the magnetic field (Hysteresis effects). Assume a proton cycle is followed by lepton cycles (Fig.1): without the lepton cycles the current in the main bending magnets goes directly to its value at the injection level. The magnetic field at this level changes by a substantial amount if the cycle sequence is changed (2 Gauss which corresponds to 0.3%) and the beam is lost. It was also observed that even slight changes of the maximal field in the lepton cycles (about 10 Gauss) can change the magnetic field at proton injection and deteriorate the transmission of the protons. By ramping the magnets always to a field which corresponds to an energy of 23.5 GeV (after the end of the beam-in segment) this sensitivity could be reduced. Slight changes during the lepton cycles have no adverse effects on the protons.

In the assembly of the supercyle other requirements have to be met. The SUPERCYCLE has to be compatible with the cycling of the CPS, which is the injector for the SPS. In addition, the total power consumption must stay below a certain value.

5. The output of the SUPERCYCLE generation

The output of the SUPERCYCLE generation is written into a standard data structure using the data structure management system MOPS and an entry in a catalog with all available SUPERCYCLEs is generated. This includes the full information about all functions needed to drive the hardware. In addition data concerning the timing system are written. Other information, like the beam-optics at each point in the SUPERCYCLE, can also be retrieved from the generated data.

6. First experience with multicycling

The SPS started to operate in multicycling mode in 1987. The lepton cycles are running on the base of the data provided by the SUPERCYCLE generation. The proton cycle is still driven in the conventional way.

The first objective was to decouple the lepton cycles from the proton cycle to allow for lepton injection and acceleration tests without disturbing the protons. This could be achieved although the proton cycle had to be reoptimized in the presence of the lepton cycles because of the change in the magnetic history. The expected effects from eddy currents (induced currents in the beampipe caused by the change of the magnetic field after a beam-in segment) are relatively small. The decay of the eddy currents causes a tune change at the lepton injection level of about 0.02 between the injection and the start of the ramp 200 ms later.

7. Summary

The SUPERCYCLE generation software can be understood as one element in the software used to study and operate the SPS. This software includes a data base (ORACLE) which contains a description of the machine and the equipment and programs to study beam physics (e.g. to calculate optics, tracking etc.). In the framework of the control system other programs for closed orbit corrections, tune and chromaticity trims etc. are available. The SUPERCYCLE generation connects the data from the database and our present knowledge on machine physics to prepare the parameters needed to drive the accelerator and serves as an interface between theoretical models of the accelerator and the hardware settings. In this sense the SUPERCYCLE generation is a step towards a coherent software structure for the CERN-SPS.

8. Acknowledgement

We would like to thank L.Evans for his contributions and many innumerable discussions.

9. References

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