Accelerating with solid core magnets

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ABSTRACT - The CELSIUS ring in Uppsala is a combined cooler storage ring and slow-cycling synchrotron. The dipole magnets are made of solid (non-laminated) steel. Therefore high eddy currents are induced in the steel while the magnetic field is changed rapidly. A method to eliminate the effects of the eddy currents has been developed. A total of 24 parameters are controlled by vector tables. This means that each power supply can be programmed to follow a specific curve during a machine cycle. The main winding generates the dipole field, back-leg windings are used to correct the dipole field in the end magnets and pole-face windings are used to correct the field distribution. These parameters are updated by an iterative procedure where each iteration includes measurement of field and field distribution during a machine cycle, calculation of differences between measured values and desired values and calculation of new vector tables such that a better result is obtained in the next machine cycle. Other parameters such as quadrupoles and RF-frequency are calculated directly from the dipole field. A description is given of the built-in field measurement system, the correction windings and the procedure to prepare the ring for acceleration.

INTRODUCTION

The CELSIUS ring produces cooled and accelerated ions for nuclear and particle research. It consists of four 90^0 bending sectors and four straight sections. Each quadrant has 10 dipole magnets with alternating gradients (F-magnets and D-magnets) made of solid steel. All 40 dipole magnets are exited by a main winding. There are also correction windings. 12 of the magnets have back-leg windings to correct the dipole field. Four of the magnets in each quadrant have pole-face windings to correct the field distribution. Both the gradient and the sextupole component of the field can be corrected.

A typical machine cycle consists of injection, acceleration, experiment and decceleration. After injection the field shall be changed as fast as possible to the field level determined by the experiment, and remain constant as long as the experiment continues. This can be achieved by a correct programming of the magnet current as a function of time.

The eddy currents will give a different contribution to the dipole field in the end magnets than in the other magnets. If not compensated these errors would produce a closed orbit distortion and beam loss. These errors can be eliminated by a correct programming of the currents in the back-leg windings.

The eddy currents will also contribute to the multipole components of the field. If not compensated these errors would cause tune shifts, resulting in resonances and beam loss. It is possible to eliminate these errors by a correct programming of the the currents in the pole-face windings.

To find all these currents as a function of time we use an automatic iterative procedure where each iteration includes measurement of field and field distribution during a machine cycle, calculation of differences between measured values and desired values and calculation of new vector tables such that a better result is obtained in the next machine cycle.

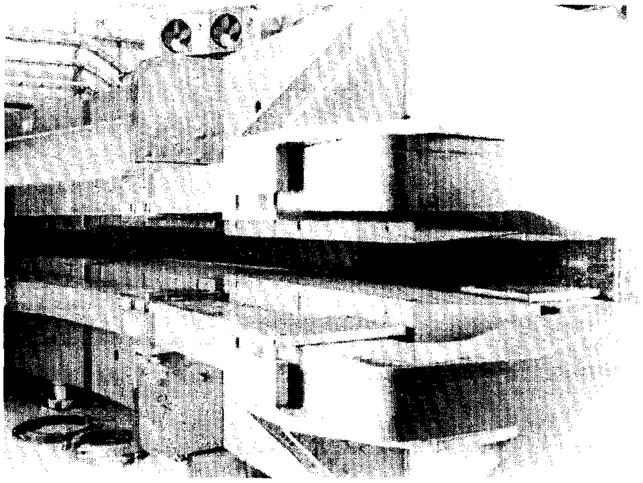

Fig. 1. D-magnet at end of one quadrant

THE FIELD MEASUREMENT SYSTEM

In one of the quadrants a field measurement system is installed.The measurement quadrant is divided into four groups as follows.

Group	Magnet	poleface winding	back-leg winding	flip-coil
1	D40	X	X	
	F41			
2	D42	X		
	D43			
	F44			X
3	D45	X	X	
	F46			
4	D47	X		
	D48			
	F49		X	

Group 2 has no back-leg winding and is used as the reference group for dipole field measurements. In each group we want to measure the dipole field, the gradient and the sextupole component of the field.

The change of the field is measured with stationary pick-up coils. The pick up coils are made as a pattern on a double-sided cirquit board. Each board consists of three coils placed at three different radial positions. The boards are mounted on the upper pole faces of all magnets in quadrant 4 and the middle coils are placed at the central orbit position.

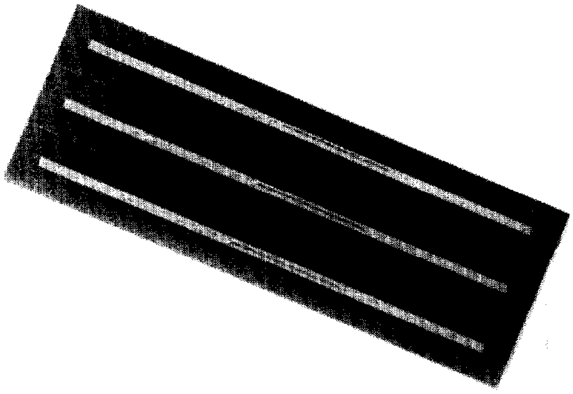

Fig. 2. Pick-up coils.

The signal from the middle coils is integrated and gives the change of the dipole field.

$$B(t)-B(0) = \int_{t=0}^{t} NA\frac{d\Phi_0}{dt}dt$$

where
NA is the total flux-collecting area
Φ_0 is the flux at central position

The outer and inner coils are used to measure the gradient and the sextupole component of the field.

To know the dipole field at the time when the integration starts we use a flip coil and an integrator. The initial values of the gradient and the sextupole component of the field are known from static Hall-plate measurements and are read by the computer from a data file.

The integrators we use were developed at the LEP division in CERN. The signal from the pick-up coils is amplified and added to a +5 V reference voltage. This signal is fed to a 100 kHz V/f converter. The output pulses from the V/f converter are counted by a 32 bit counter. A reference frequency of 50 kHz is counted by another counter. The G64 microcomputer reads the two counters and subtracts the two readings. In this way a bipolar integrator is obtained. The counters are read when a trigger signal comes. At the same moment the counting is switched over to another set of counters.

Each group has a rack containig three integrators, a preamplifier and a G64 micro computer. Rack nr 5 contains the integrator for the flip-coil and a G64 micro computer system which triggers all the integrators, collects the data from the other four racks and sends the data to the main computer. The flip-coil is flipped once per machine cycle (at time=0) and the integrator is read in both positions (clockwise and counter-clockwise).

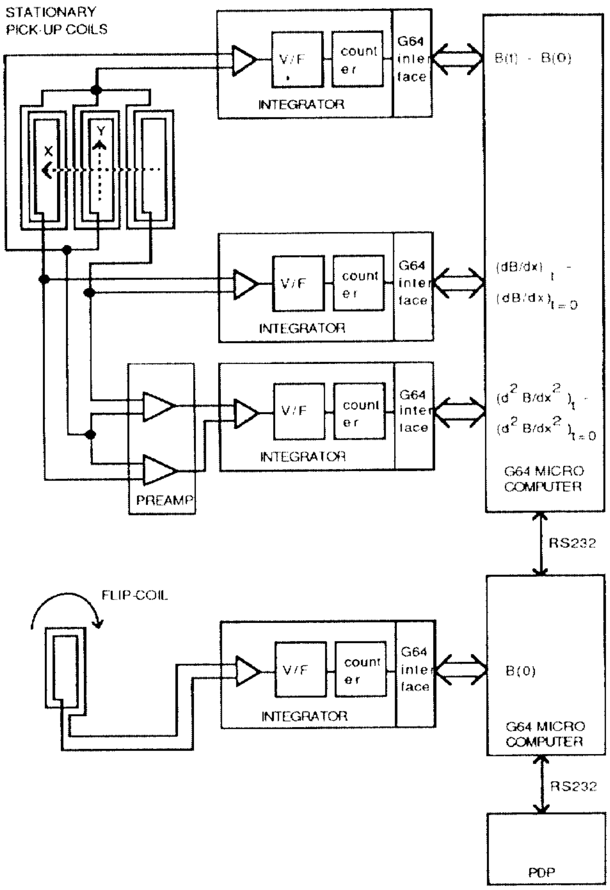

Fig. 3. Block diagram of the field measurement system

PREPARING THE RING FOR ACCELERATION

Static mode

The procedure to prepare the ring for acceleration starts by tuning up all parameters in static mode. The magnetic field is determined by the energy and the charge state of the particles delivered by the injector cyclotron. The stored beam intensity and lifetime is optimized with the following constraints:

keep the tunes at the desired working point
keep the relation between magnetic field and RF-frequency (keep the cirqumference constant)
keep the beam on the desired closed orbit

When the optimum settings have been found the flip-coil is flipped and read. A program reads the settings of all static parameters and updates the indata files needed for the programs which update the vector tables.

Iteration of the field

The specifications of the desired dipole field cycle are entered to an indata file. If the breakpoints during the cycle are new or if the desired field levels are changed a lot, a program is run which creates new vector tables by analytical formulae. Then the cycling of the magnets is started. After a few cycles the field is reproducible from cycle to cycle. Then the iteration program is started. The program reads the measurement file of the previous cycle, corrects data for effects not seen by the measurement system and calculates the difference between the measured and the desired dipole field in the reference group. Then new vectors are calculated and loaded to the database and to the function generator of the power supply for the main winding. Then the program waits for the end of the next measurement cycle and the procedure is repeated until the error in the dipole field is small enough. It takes typically 10 iterations to reach a field which differs from the desired field by less than 0.0001 T at any time during the cycle.

To optimize the injections we introduce a small linear ramp of the dipole field a few seconds around the desired injection moment. Then we inject with high pulse repetition frequency and can see at what time the injections are best. Then we go back to single pulse injections and move the injection moment to the time which gave best injections.

The desired dipole field in one of the other groups of the measurement quadrant is a constant factor times the dipole field in the reference group. This factor is found from the back-leg winding current in the static case. To find the back-leg winding current which gives the desired dipole field the iteration program is used again. The same procedure is repeated until the error in the dipole field of any group is small enough. This takes typically 5 iterations. Then the back-leg currents for the other quadrants are calculated from the back-leg currents of the measurement quadrant.

Finally the currents of the pole-face windings are iterated to keep the measured values of K_1 and K_2 constant in each group (K_1 is the gradient normalized to the magnetic rigidity and K_2 is is the sextupole component of the field normalized to the magnetic rigidity).

Experience has shown that it is also possible to calculate the currents of the pole-face windings and of the back-leg windings directly from the dipole field and the current in the main winding with sufficient accuracy.

Quadrupoles and RF-frequency

To calculate the currents of the quadrupoles and the RF-frequency we need a measurement of the dipole field with better time resolution. For this purpose we use a separate measurement channel where the dipole field of the reference group is measured with a time resolution of 50 ms.

A program reads this fast B-measurement file, corrects data for effects not seen by the measurement system and calculates vector tables for the quadrupoles and the RF-frequency. Using vector tables means that we introduce a linearization error. To minimize this error the length of each vector is calculated to give a linearization error smaller than a selected maximum error. The maximum number of vectors has been increased to 256 by running four 64-vector tables per cycle.

RESULTS

The first acceleration attempts started in spring 1989. Since then protons have been accelerated to a maximum energy of 1 GeV. At 600 MeV the maximum nr of stored protons has been 5 x 10^9.

The main difficulties have been to calculate the RF-frequency with sufficient accuracy and to keep the tunes constant during acceleration. These problems have been solved by adding artificial bumps in the calculated vector tables.

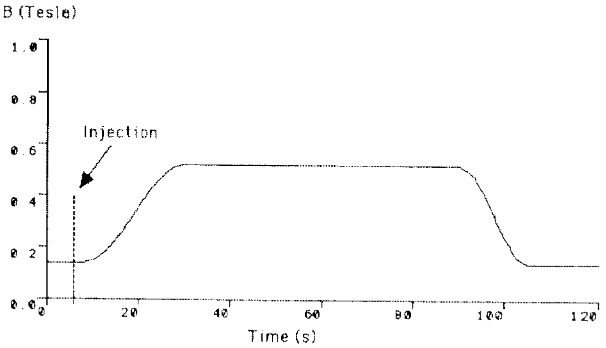

Fig. 4. Dipole field cycle for acceleration from 48 to 500 MeV

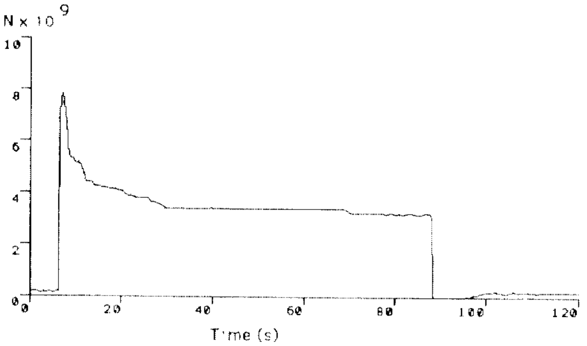

Fig. 5. Number of stored protons during acceleration to 500 MeV

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