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CONTROL OF FERMILAB BOOSTER TUNES

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Summary

Control of the radial and vertical tunes of the Booster is implemented using ramped correction quadrupoles. Minor modifications to the power supply cards for the 48 (previously) d.c. correction quadrupoles allow the tunes to be continuously programmed or held constant throughout the 33 ms acceleration cycle. This capability is in addition to the usual use of these quadrupoles to be independently varied to correct for harmonic distortions in the lattice. An automatic computer program measures and displays the tunes vs. time in the cycle to monitor performance and to allow the ramps to be adjusted by the machine operator.

Introduction

Nominal horizontal and vertical tunes in the Fermilab combined function Booster with no correction quadrupoles are $\nu_h = 6.7$ and $\nu_v = 6.8$ respectively. Air-core correction quadrupoles are added which are designed for a maximum tune shift of ±.6 at injection[1]. Twenty-four quads are located in short straight sections where β_h is maximum and twenty-four are in long straight sections between periods where β_v is maximum. As originally installed the quads run at individually variable DC currents. Hardware has since been added which forms 2 analog ramp waveforms used to control the tunes through the cycle. One waveform is bussed to the quads at $\beta_h$max locations (Q short), and one is bussed to the $\beta_v$max quads (Q long). The new hardware consists of four camac modules used for ramp generation and a module containing ordinary operational amplifiers for conversion of the camac ramps into a useable form. Summing junctions were added to the individual quadrupole control cards.

TABLE I

Quads	β_h	β_v
Q short	33.7 (max.)	5.3
Q long	6.5	20.1 (max.)

Ramp and DC Hardware

A camac 091 timing module and a 150 function generator module are used together to construct an 8 segment, 0 to 10.24 volt ramp. The 091 module has an 8 word 24-bit memory which stores delay data for eight software-variable trigger outputs[2]. This module advances the 150 module through a 16 word (16-bit) readable and writeable memory containing information for 8 levels and 8 slopes. The ramp segments are variable in time, amplitude, and slope, where slope information controls the ramp rate of change between successive segments.

Correction quad hardware consists of a current regulating PC card driving a pair of bank mounted power transistors for bipolar output of each quad. Control voltage range is ±10 volts, so the camac generated waveform is converted from 0-10.24 volts' to a ±10.24 volt drive waveform in modulating hardware which performs the function V out = 2 x (V in - 5 volts). The output voltage (waveform) is summed at the regulator PC card with the individually controllable DC voltage. The resultant current in each quad is then a waveform common to all quads of its type plus its own DC current.

Quad Control Software

The DC currents of each quad are variable from a console program which allows correction of azimuthal harmonics resulting from gradient errors in the lattice. First through 24th harmonic corrections are controlled in amplitude and azimuthal phase. Figures (1) and (2) show DC quad currents as a function of location around the 24 cell Booster for 1st harmonic corrections at 0° and 90° phases respectively (phase is referenced to period 1 short straight section).

A second program allows display and control of time, amplitude, and slope information for the 8-segment ramps. The program features a save and restore option allowing recovery of all parameters. Values proven good for machine operation are stored for future use along with a brief descriptive text. Ramps can be turned on and off from the console, thus returning all quads to their respective DC levels. Because the sum of ramp and DC control voltages could exceed the ±10.24 volt regulator card range, the software limits ramp amplitude values so that no quad receives a total control voltage outside this range. This feature preserves harmonic tuning of DC levels. Figure (3) shows ramped currents for an arbitrarily chosen quad of each type.

Tune Measurement - Hardware

The Booster uses 10-turn rectangular ferrite transformers located in one long straight section to detect coherent betatron oscillations of the beam. Currents in opposite winding pairs are filtered above 10 MHz and amplified in the Booster enclosure. Signals from the horizontal and vertical windings are converted to TTL logic pulses by a zero crossing detector in a tune measuring module in the control room. A TTL pulse train representing the beam revolution frequency is a third input to the tune module. Revolution frequency, and horizontal and vertical betatron pulses then strobe counters to a limit preset by a thumbwheel switch to a number N. The counters generate gates proportional in length to the times necessary for each to count pulses up to the preset value. The actual time lengths of the gates are measured by gated counters and a 10 MHz oscillator. The resulting ratio of

$$\frac{\text{Time for N Revolutions}}{\text{Time for N Betatron pulses}} \quad \text{is}$$

calculated in the Booster computer to give the fractional parts of the Booster tunes. The time module is triggerable to allow tune measurement through the entire Booster cycle.

Coherent betatron oscillations are induced in the beam with single turn ferrite kicker magnets called notchers. The 44 inch magnets are 50 ohm transmission

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*Operated by Universities Research Association Inc. under contract with the Energy Research and Development Administration.

line-type with fields of up to 80 gauss, rise times of ~25 nsec, and pulse lengths of ~1.8 μsec[3].

Tune Measurement - Software

A console program for tune measurement automatically sets the notcher firing time, notcher field strength, and tune start time to tabulated values and stores the resulting measured tune values. Horizontal and vertical tunes can then either be plotted as a function of time or displayed on a tune diagram[4]. Time plots of Booster tunes are illustrated by figures 4 and 5. Figure 6 is the same data displayed on a tune diagram showing containment of the tunes within the stable working diagram bounded by the resonance lines ($\nu_x = \nu_y$), ($2\nu_x - \nu_y = 7$), and ($2\nu_y + \nu_x = 20$). When the ramped quads first became operational they were adjusted to contain the tunes in the shaded area labeled (1). This area was chosen simply because of its closeness to the nominal Booster tune values.

Studies done at the Booster injection energy of 200 MeV indicated a significantly longer beam lifetime at higher horizontal and vertical tune values. For this reason the ramped quads were retuned to shift the working point to shaded area 2 on the tune diagram. This tuning resulted in a subsequent reduction of vertical beam size at extraction by approximately 20% for intensities above 2.0 x 10^{12} protons per pulse.

References

1. E.L. Hubbard, et. al.

2. J. Simanton, Control note, 12/12/74.

3. See reference 1.

4. Warren Light, Controls Software Release No. 5, 7/11/76

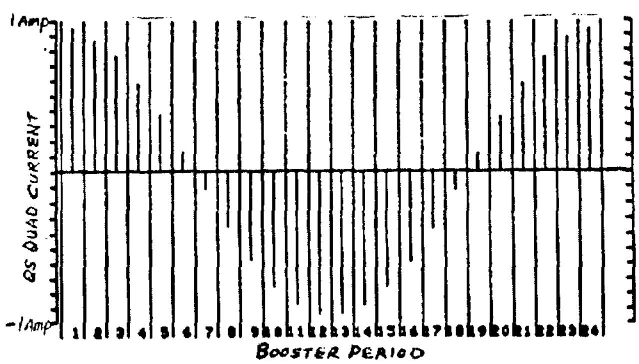

Fig.1 DC quad currents at period short straight sections for 1st harmonic correction with 0^0 phase advance.

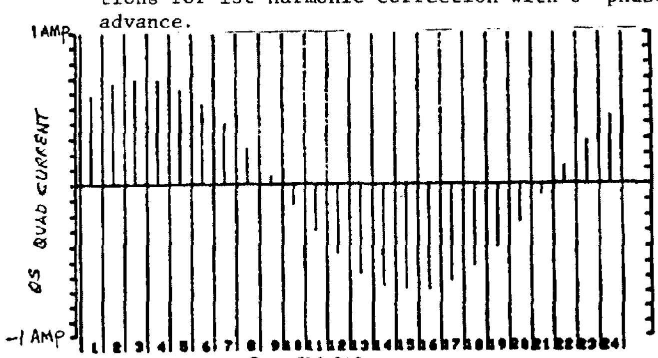

Fig.2 DC quad currents at period short straight sections for 1st harmonic correction with 90^0 phase advance.

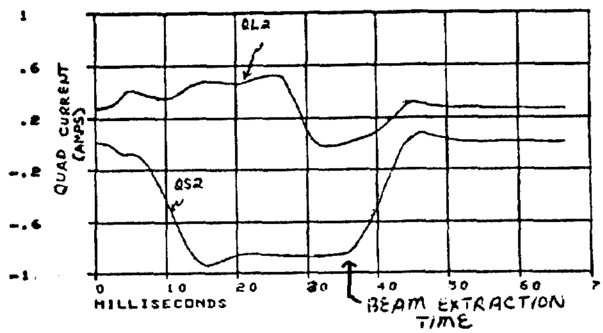

Fig.3 Ramped current waveform of QL2 (β_v max) and QS2 (β_h max).

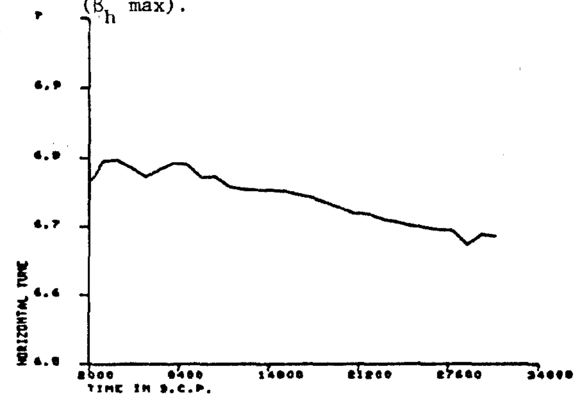

Fig.4 Horiz. tune vs. time in cycle for ramp waveforms of Fig.3.

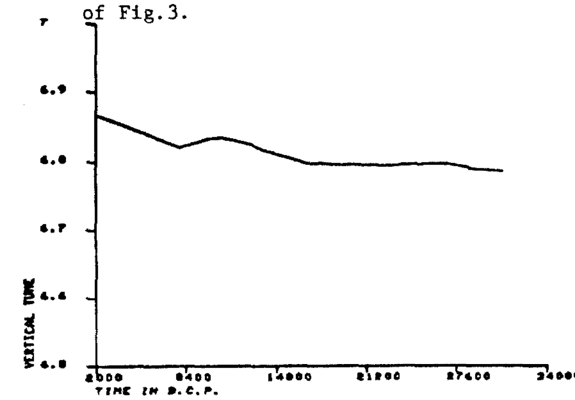

Fig. 5 Vert. tune vs. time in cycle for ramp waveforms of Fig.3.

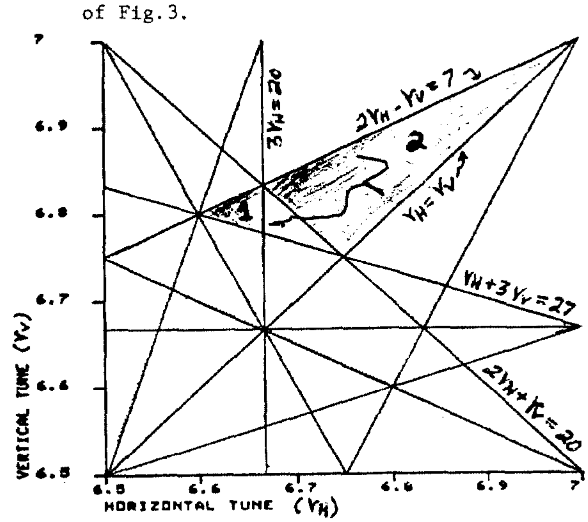

Fig. 6 Plot on tune diagram of tunes in Figures 4 and 5.