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COORDINATED CONTROL OF THE ENERGY AND TIME DEPENDENT PARAMETERS OF THE TEVATRON*

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Summary

The computer program used to control the time and energy dependent parameters of the Tevatron is described. Using mathematical models of the machine systems, the program allows the operator to vary the ramp characteristics, the rf, and magnetic correction elements. The timing system is automatically modified to reflect new ramp variables. Graphic displays show the consequences of changes in the limiting factors of the machine, desired operating conditions, or the machine model. These displays include the desired changes, the derived values (such as synchrotron frequency and bucket area) and the actual function generator outputs for the corresponding devices. The program has been designed to change or "tune" the operating parameters quickly and to allow considerable flexibility for diverse machine development experiments.

Introduction

Need for Fast Changes

The Fermilab Tevatron has been designed to operate as a 400 GeV accelerator in an energy saver mode, a 1000 GeV fixed target machine, and a proton-antiproton collider. In addition many of the components needed for these activities are expected to come on-line sporadically. Thus a variety of changing operating modes and conditions is certain, especially considering the experimental nature of the superconducting magnets and associated refrigeration system.

As well, the different uses of the Tevatron ring argue for a flexible control system to perform many different types of machine experiments.

Since any change in the operating modes and/or conditions can have far-reaching and sometimes obscure ramifications it is essential to coordinate the ramp, rf parameters, correction elements, and timing changes.

Constants

Included in the subject of man-machine communication is the question of the constants used in the calculations to determine hardware settings given the desired machine parameters. These range from the machine radius and transition gamma to constants to convert from function generator output voltage to frequency. The program described here provides a framework for entering and modifying these data.

Some data from "bench tests" have been included as well. For example, the measured multipole moments of the 774 dipoles installed in the Tevatron were parameterized and used in the calculations of the correction element settings for tunes and chromaticities.

With all data available in one program, the consequences of any change of operating conditions can be checked for error even down to the hardware level; e.g. power supply ramp rates and function generator table limits.

Color graphics displays for immediate feedback and an on-line documentation system have been used extensively in the program described here and found to be essential.

Machine Model

In the following discussion the concept of a machine model is expanded from the usual definition of the lattice parameters as derived from SYNCH or TEVLAT[1] programs. Here we include all the numbers needed to convert operator desires into function generator waveforms and magnet currents. For the most part, the numbers are not coded into the program but are saved in a file which can be easily manipulated by the operator.

Ramp

The main bus of the Tevatron includes 774 superconducting dipoles, 216 superconducting quads, and some other magnets used for extraction and the beam abort. The power supplies in this circuit are controlled by a microprocessor(TECAR) which also monitors the quench protection circuitry. The current waveform ('ramp') and the constants necessary for the regulation and control of the power supplies and quench protection tests are entered and transmitted to TECAR by means of the program described here.[3]

At present, up to 32 parabolic sequences are allowed to describe the main bus waveform.

At the start of each ramp some section of the quench protection system can be tested. That is, some subset of the SCRs which bypass current around a 10 magnet string in the event of a quench can be turned on and checked before the machine is ramped to full energy. To reset the SCRs before the full ramp the current flow must be reversed; the TECAR waveform is automatically provided with the appropriate sequences for this.

Based on measurements at the Magnet Test Facility (MTF), the sextupole moment of the dipoles is more reproduceable if the magnets are brought to a 90 GeV level before each ramp.[4] This is a normal feature of the waveform sent to TECAR.

RF

The RF system is controlled by 11 function generators which are used to vary the rf frequency and phase(2), phase feedback strength(2), high voltage (5), and the cavity tuning(2).[2]

The change of the 53 MHz RF frequency is about 1kHz as the energy is varied from the 150 GeV injection level up to 1 TeV. The energy variation of the rf frequency is controlled by a microprocessor with desired changes of radial position offset added using the first of the function generators.

The high voltage control includes the anode supply, the driver grid bias and the power amplifier grid bias.

With such a small fractional change in RF frequency it is possible to tune the cavities by changing their temperature. Two feedback loops in the cooling water circuits are used to control the temperature of the cavities. The first uses bypass valves (8 s delay) and the second uses electric heaters (1/2 s delay) near the cavities. The function generator curves mentioned above provide advance information to the feedback circuits to reduce the amount of energy required by the heaters.

Tunes and Chromaticities

There are presently 5 superconducting circuits for controlling the betatron tunes of the Tevatron. Two circuits of correction quadrupoles, one set near the focusing quads of the main bus and the other near the defocusing quads, are used to control the horizontal and vertical tunes. Two circuits of correction sextupoles, similarly arranged, control the horizontal and vertical chromaticities. The fifth circuit is of correction skew quadrupoles and controls the coupling of the horizontal and vertical betatron motion.[5]

The conversion of the desired tune values entered by the operator into actual current waveforms for these 5 circuits involves knowing: a) the relative strengths of the circuits, b) the machine lattice (e.g. average beta values at the correction element positions give the coupling constants needed for orthogonal control of the horizontal or vertical tune), and c) the contributions of the energy dependent multipole moments of the magnets in the ring. For the last item, the appropriate multipole measurements of all the dipoles installed in the ring were averaged and fit to polynomials and incorporated into the conversion algorithms. All coefficients are available to the operator to modify as results of machine experiments refine the data.

Half-integer Extraction

The half-integer resonant extraction is controlled in part by 6 superconducting circuits. These are two 39th harmonic quad circuits, two 39th harmonic octupole circuits and two 0th harmonic octupole circuits. Of course, the ordinary tune circuits are also involved in the extraction process. However, since extraction takes place at constant energy, the necessary waveforms are simple. So far, the settings have been determined empirically without too much trouble.

Timing

General timing signals, called clock events, are broadcast throughout the site using a 10 MHz clock system. Those events which change with different ramp waveforms are automatically recalculated and sent when a new operating condition is activated. The calculation algorithms can be based on time and/or energy in the cycle or referenced to other clock events.

There are 216 correction dipoles for correcting the Tevatron closed orbit. Since the high field orbit is not correctable in the usual way(i.e. moving quads), these elements are rather strong and must be programmed throughout the cycle. Most of these corrections are proportional to the energy of the machine and are taken care of automatically in the case of a new ramp by the signal sent by TECAR and the energy dependent table of the dipole function generators. Some time dependent tables, e.g. for injection and extraction, exist in these same generators and must be changed if the main ramp waveform is modified. When a new ramp is generated, new breakpoints for the time table are calculated and sent to a program operating in the central computer which resets the necessary tables.

Calculational Algorithms

Sequences, General Discussion

The idea of a control program which allows one to construct waveforms from modular calculational elements using terms familiar to accelerator physicists is not new. A similar program is used to control the CERN Antiproton Accumulator's two waveform generators to vary the RF voltage and frequency.[6] However the scope of the program described here is somewhat different in that there are 23 separate waveforms controlled directly, up to 216 which are controlled indirectly, and up to 32 directly controlled timing channels.

Operators of the machine are able to enter desired waveforms by specifying up to 18 different sequences. A sequence is a calculational algorithm for determining how parameters are to vary from the end of the preceding sequence over the time interval of the sequence. The time interval itself may be entered explicitly or calculated. A sequence usually corresponds to a subroutine of the program and is rather easy to redefine or invent. The following sequences are those used at present but should be considered as examples as they are easily modified. Fig. 1 shows the TV image that the operator uses to construct the main bus and RF waveforms. For a particular type of sequence some of the entries on a row are input (indicated by inverted fields on the TV screen but here by a > to the left of the number); the others are calculated results.

```
T49  MODIFYing file 1  512 GEV!5 SEC FT NEW QX, QY
*Return *ch-plot *ch-calc *RAMP/RF *tune    *extract *timing  *send
*Help                     *CALC/PL *insert  *delete
   CYCLE TIME 50  s,    MAX RF 1   Mev/turn,      MAX RAMP 25  GeV/s
                 ---------------values at end of sequence----------------
SEQ TYPE     Dt      ENERGY   TIME     RPOS   AREA   PHI    f      HV     Edot
 1 INIT( >  4.65 >149.73   4.65     0    > 1      0      0      .057> 0
 2 MPARAB   .9816>162      5.632    0    > 1      36.0   152    .075> 1
 3 PARAB    13.52>500      19.15>   0      1      45.0   949 >  .731> 1
 4 MPARAB   .96   >512     20.11    0    > 1      1.14   954    .019> 0
 5 CAPDEP>  5     >512     25.11>   0    > 1      1.14   954    .017> 0
 6 PARAB    1     >502     26.11>   0      0      0      950 >  0     >-.8
 7 PARAB    20.1  >100     46.21>   0      0      0      -1295> 0     >-.8
 8 PARAB    1     >90      47.21>   0      0      0      -1043> 0     > 0
```

Fig. 1 Sequence Control Page for RF/RAMP parameters. An example of a 512 GeV ramp with 5 second flat-top.

The columns are: 1 sequence number, 2 sequence type, 3 time interval of the sequence in seconds, 4 energy in GeV, 5 time from waveform reset, 6 radial position in mm, 7 bucket area in eV-s, 8 synchronous phase angle in degrees, 9 rf frequency relative to that at injection in Hz, 10 high voltage in fraction of the maximum, 11 dE/dt in fraction of the maximum. The maximum voltage and ramp rate are entered on the 4th row of the page; thus if a power supply or rf cavity fails, only one number needs to be changed to allow the entire set of waveforms to be recalculated and activated.

Sequence insertion or deletion modes are controlled on row 3. The default mode is to calculate and plot all sequences down to the cursor position if the cursor is in the lefthand column when the interrupt is pushed.

Sequence Definitions

The INITIAL sequence starts all ramp definitions and is used to set the zero level of the function generators. The quench protection tests and the change from the 90 GeV magnet reset level to the 150 GeV injection level are inserted into the TECAR table.

The PARABola sequence has as input the final energy, dE/dt, radial position and high voltage. The four boundary conditions (initial and final energy, initial and final dE/dt) determine the time interval Dt and A, B, and C, where E = At**2 + Bt + C. The high voltage and radial position are varied linearly over Dt.

The Matching PARAbola sequence requires the final energy, dE/dt, and bucket area. It determines the main bus current in the same way as the PARAB sequence. However it changes the high voltage (HV) in such a way as to vary the rf bucket area linearly from initial to final values. This is done using a 7th order polynomial fit to alpha(sin(phi)) to solve the two simultaneous equations

dE/dt=c1*HV*frev*sin(phi) and
bucket area=c2*alpha(sin(phi))*SQRT(E*HV/eta).

The resulting 14th order polynomial is solved iteratively using Newton's method.

The CAPture-DEPosit sequence takes place at constant energy and has the time interval and final bucket area as inputs. The time dependence of the area is

A(t)=Ai/(1-((t-ti)/(tf-ti))*((Af-Ai)/Af))

This gives a constant adiabaticity, (dA*Ts)/(dt*A), where Ts is the synchrotron period, Ai (Af) is the initial (final) A, and ti (tf) is the initial (final) time.

Other Program Features

The second row of the page shown in fig.1 contains branches to other program options. Ch-calc, or change calculation constants, is where the operator may change the machine model. Fig. 2 shows the work page for the rf and main bus, or ramp, parameters.

```
T49  Accelerator Constants
*Return
*Help     160 Module constants, rf frequency, phase
Radial Position: V(1)= 0          + 1        *RPOS
E*Rdot          : V(2)= 0          + 1        *E*Rdot)/E
Error Gain 1    : V(3)= 0          + 1        *E
Error Gain 2    : V(4)= 0
          160 Module constants,     High Voltage
Anode Program 1: V(5)= 0          + 1        *HV
Anode Program 2: V(6)= 0
Driver Bias 1   : V(7)= 0          + 1          rf on, off
Driver Bias 2   : V(8)= 0
PA Grid Bias    : V(9)= 0          + 1        *HV
          160 Module constants,     Cavity Tuning
H2O Valve Prog : V(10) 0          + 1        *HV(to)**2
H2O Heater Prog: V(11) 0          + 1        *HV**2
                         0          + .5        (delay, t disp
           TECAR constants: Dipsy-do levels(%,GeV)
 EREST 90      ETEST  90     ERESET  90
 QDSSL 10             4.44    DTEDD  1
           TECAR constants: Load constants L,R,V
    L= .709          R= .0033       V= .45
```

Fig. 2 Work page for entering calculational constants for RF/RAMP parameters.

Ch-plot, or change plotting parameters, controls the graphics screen. Plot variables, limits, and colors can be chosen for up to 4 calculated values and 4 analog signals. An example for the sequences above is shown in fig. 3. In addition to the variables shown on the sequence page and their corresponding analog signals, other derived curves such as synchrotron frequency and adiabaticity coefficient are also available. Fig. 3 shows the variables available for RF/RAMP displays.

```
T49  Change-Plot Parameters
*Return   *Ydiv=5  *Xdiv=10 Colors=YRCG DevColors=YRCG
*Help  Param Title  Min     Max      Devices
X:Time From Reset : 0     : 50     | :
1:Energy,GeV        : 0     : 520    |1:T:ERING
2:High Voltage,MV  : 0     : 1      | :
 :Bucket Area,eV-s: 0     : 10     | :
 :Phi sub s,Deg     : 0     : 10     | :
 :RF Frequency,Hz  : 0     : 1000   | :
4:Synch Freq,Hz     : 20    : 70     | :
 :Adiabaticity      :-.1    : .1     | :
3:Radial Pos(t)     :-10    : 10     |3:T:RPGM
 :I*Pdot(t)          :-10    : 10     | :T:IRDOT
 :Error Gain(I,t)  :-10    : 10     | :T:ERGN1
 :Error Gain(Idot):-10    : 10     | :T:ERGN2
 :Anode Prog(I,t)  : 0     : 10     | :T:APG1
 :Anode Prog(Idot): 0     :-4.618 | :T:APG2
 :Driv Bias(AP,t)  : 0     :-8      | :T:DRGB1
 :Driv Bias(Fs,t)  : 0     :-8      | :T:DRGB2
 :PA Bias(AP,t)    :-10    : 10     | :T:PAGB
 :H2O Valve(t)      : 0     : 10     | :T:WVPGM
 :H2O Heater(t)     : 0     : 10     | :T:WHPGM
```

Fig. 3 Plotting control page for RF/RAMP sequences. Up to 8 variables and colors are possible.

Fig. 4 shows the graphics output for a sample choice of RF/RAMP variables.

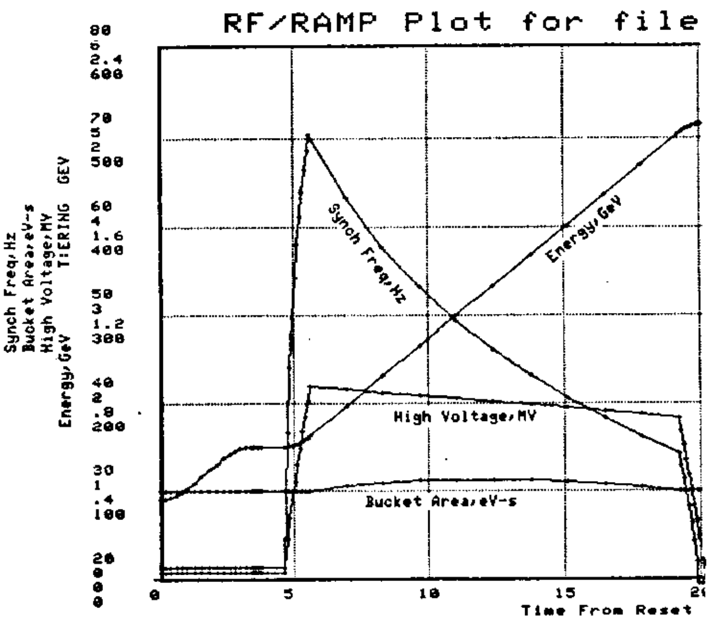

Fig. 4 Color graphics display of results of the sequence calculation defined in fig. 1.

On each of the 19 control pages for changing sequences, constants or plotting control there is a help option. Interrupting with the cursor under this word causes a page of instructions/information to be displayed on the TV screen for that particular control page. The text is easily edited and saved.

Tune and Extraction Control

The LINEAR sequence is used mainly for control of tune and extraction power supplies. Since the currents in these circuits are largely proportional to the machine energy, the time breakpoints of the curves are determined by the RF/RAMP sequences. The values typed in by the operator are linearly interpolated over the sequence time intervals.

Fig. 5 shows the sequence page for tune control and fig. 6 shows the corresponding work page for entering the machine model constants.

```
T49  MODIFYing file 1  512 GEV15 SEC FT NEW QX, QY
*Return *ch-plot *ch-calc *ramp/rf *TUNE    *extract *timing  *send
*Help                     CALC/PL   breakpoints as in rf/ramp
   CYCLE TIME 50  s,    MAX RF 1   MeV/turn,      MAX RAMP 25  GeV/s
              ---------------values at end of sequence---------------
SEQ TYPE    Dt     ENERGY  TIME  QX       Qy        CX     CY       skewQ
 1 LINEAR  4.65    149.7   4.65 >19.445>19.374>  18.5 > 6       >-1.32
 2 LINEAR  .9816   162     5.632>19.445>19.374>  25.5 >-2       >-1.369
 3 LINEAR  13.52   500     19.15>19.468>19.374>  34.8 >-30      >-2.15
 4 LINEAR  .96     512     20.11>19.468>19.374>  35   >-29      >-2.15
 5 LINEAR  5       512     25.11>19.468>19.374>  35   >-29      >-2.15
 6 LINEAR  1       502     26.11>19.468>19.374>  35   >-29      >-2.15
 7 LINEAR  20.1    100     46.21>19.445>19.374>  18.5 > 6       >-1.32
 8 LINEAR  1       90      47.21>19.445>19.374>  18.5 > 6       >-1.32
```

Fig. 5 Control page for horizontal and vertical tunes and chromaticities and the skew quadrupole setting.

```
T49  Accelerator Constants
*Return
*Help           Tune HOG calculational parameters
Tunes
    4Qh =-19.4          + 0       E      + 0        E**2     + Qh
    4Qv =-19.4          + 0       E      + 0        E**2     + Qv
  <b1> = 1.56           +-.243    E      + 0        E**2
         + 0      E**3  + 0       E**4   + 0        E**5
  I(1)/E= 39.6    4Qh   + 11.1    4Qv    - 0         +-3.3      <b1>
 -I(2)/E= 12      4Qh   + 43      4Qv    - 0         + 3.3      <b1>
Chromaticities
    4Ch = 22.5          + 0       E      + 0        E**2     + Ch
    4Cv = 22.5          + 0       E      + 0        E**2     + Cv
  <b2> =-23             + 205.9   E      +-671.8    E**2
         + 1071   E**3  +-831.4   E**4   + 251.2    E**5
  I(3)/E= .163    4Ch   + .047    4Cv    - 0         +-3.2      <b2>
 -I(4)/E= .087    4Ch   + .3      4Cv    - 0         + 5.1      <b2>
Skew quad
  <a1> = .0319          +-.4653   E      + 1.995    E**2
         +-2.664  E**3  + 1.36    E**4   + 0        E**5
  I(5)/E= 6.6667 SkewQ+ 0         <a1>
Circuit polarities(+1 is nominal
    I(1), 1       !I(2), 1       !I(3), 1       !
    I(4), 1       !I(5), 1       !
```

Fig. 6 Work page for entering constants to define the machine model used in the tune calculations.

Control System

The new Fermilab accelerator control system uses PDP-11/34 computers for console and front-end computations. A VAX-11/780 occupies the central node of the network. All of the computations and displays described in this paper are made in the console PDP-11. Even though this implies many program overlays, the calculations are relatively short and the console response is somewhat faster for having fewer network transfers.

A standard console is equipped with a color TV screen, large color graphics screen, touch panel, storage scope, keyboard, trackball and cursor. Program control is mostly by trackball, cursor and interrupt button, using the keyboard to enter data. 7

The graphics displays associated with the program described here are driven by an associated secondary application program which occupies a separate partition of the console computer. Plots of desired waveforms and the corresponding readbacks can be initiated by the main program and then the secondary program continues independently to gather data via the network and update the displays. This separation of the calculation and graphics drivers allows the operator to use other programs while still monitoring the behavior of some system.

Experience and Conclusions

The system described in this paper to control the time dependent parameters of the Tevatron has been used since the initial commissioning of the machine. It provides a framework for incorporating improved understanding of the accelerator for more accurate control of the tunes, chromaticities and rf parameters. It provides the usual save /restore functions and allows operating modes or conditions to be changed quickly (the time needed to calculate and load the 23 function generator tables and 32 clock event registers is less than 20 seconds for the most complex ramp yet imagined). Since the desired conditions can be specified in common units (e.g. energy(GeV), bucket area(eV-s), radial position(mm), tunes, chromaticity(natural units), etc.) in a universal format, the operation of the machine is quickly learned.

The automatic displays which compare desired and actual power supply waveforms are needed. The on-line documentation has found other uses than basic information for program operation including storage of numbers and procedures too often lost in obscure log books and communication between users and programmers(GROUSE).

Ackowledgements

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