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RHIC Ramps: a proposal

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Introduction

The non-cyclic nature of a collider such as RHIC is most evident in the way that tuning procedures such as acceleration, re-bucketing, and the low beta squeeze are asynchronously handled. Each procedure - or ramp - is begun when an "event" is transmitted around RHIC to the equipment houses. Various widely distributed pieces of equipment are requested to respond by ramping through a state transition (loosely speaking) from one state to another in a way that is consistent with hardware constraints and that avoids adverse effects on the beam. In all cases of interest here, a piece of equipment is expected to follow a waveform that it is provided by a general purpose VME card called a Wave Form Generator (WFG). Each WFG receives data from the Real Time Data Link (RTDL) line and events from the event line, and responds with a digital output.

While the output of a WFG usually goes to a piece of equipment as a setting, such as the current required from a power supply, the output may also be used to generate a variable that is reinserted onto the RTDL line. Appropriate use of this level of indirection (in which a dependent RTDL variable is a function of other RTDL values) leads to conceptual and physical simplifications in the generation of equipment waveforms.

A high level description of the proposed way to implement RHIC ramps is presented in this note as the basis for further discussions and work. It is undoubtedly incomplete and is not fully optimized. For example, the requirements of the RF system and the interests of the RHIC RF section have yet to be understood and incorporated.

The Real Time Data Link and Wave Form Generators

Since the RTDL system sets physical constraints on the organization of RHIC ramps, a brief description is in order. More details can be found elsewhere[1,2]. RTDL information is broadcast from a central facility in the 4 o'clock equipment house on a single 10 MHz self clocking serial line that serves both Blue and Yellow rings. Each data frame includes a 24 bit parameter value, an 8 bit parameter ID, 2 start and stop bits, and 1 parity bit. The 8 bit parameter ID permits up to 255 different frames to be defined. All data frames are transmitted every 1.39 ms (720 Hz).

The RHIC Wave Form Generator is described in detail elsewhere[3]. The digital output of a WFG is the sum of 3 tables, F, G and H. A convenient notation for the coefficients and arguments of these tables is given by

$$W = Sf * Rf * F(t) + Sg * Rg * G(RG) + Sh * Rh * H(RH) \quad (1)$$

where

W	is the 24 bit output value,
Sf	is a constant scale factor (for example, it might do the final conversion to Amps),
t	is time after an event, derived from an internal rate generator,
Rf	is an RTDL variable used as a multiplicative coefficient, and
RF	is an RTDL variable used as an argument in the table look-up.

The scale factors and the real time coefficients and arguments of the tables are labeled with the lower or upper case letter of the associated table. Each F table has 128 rows, and each G and H table has 64 rows. These rows are available to define the 2 dimensional data points that are used in the onboard real time linear interpolation process[4]. A WFG can store as many as 16 waveforms - 16 sets of F, G and H tables, scale factors, and multiplier and argument types. A waveform is activated on the fly according to the identity of a triggering event on the event line. A group of as many as 8 events may all launch the same waveform. Waveform parameters are all down-loadable from the Front End Computer (FEC) that controls the VME crate in which the WFG resides. The waveform output is calculated at a selectable rate of 720 Hz, 1 kHz, 5 kHz, or 10 kHz.

The vast majority of WFGs provide their output values as required settings to interface modules connected to accelerator magnet power supplies. Because of this common usage, a WFG also includes 2 digitizing channels of analog input connected to circular buffers supporting circular, pre-trigger and post-trigger recording. The maximum recording time in these buffers is 10 seconds, at a rate of 720 Hz. In addition to the 2 analog channels, digital set point loop-back data can be recorded in the same fashion. In the design for collider operation proposed here, a small subset of WFGs put their output back onto the RTDL line. This is shown in graphical form in Figure 1.

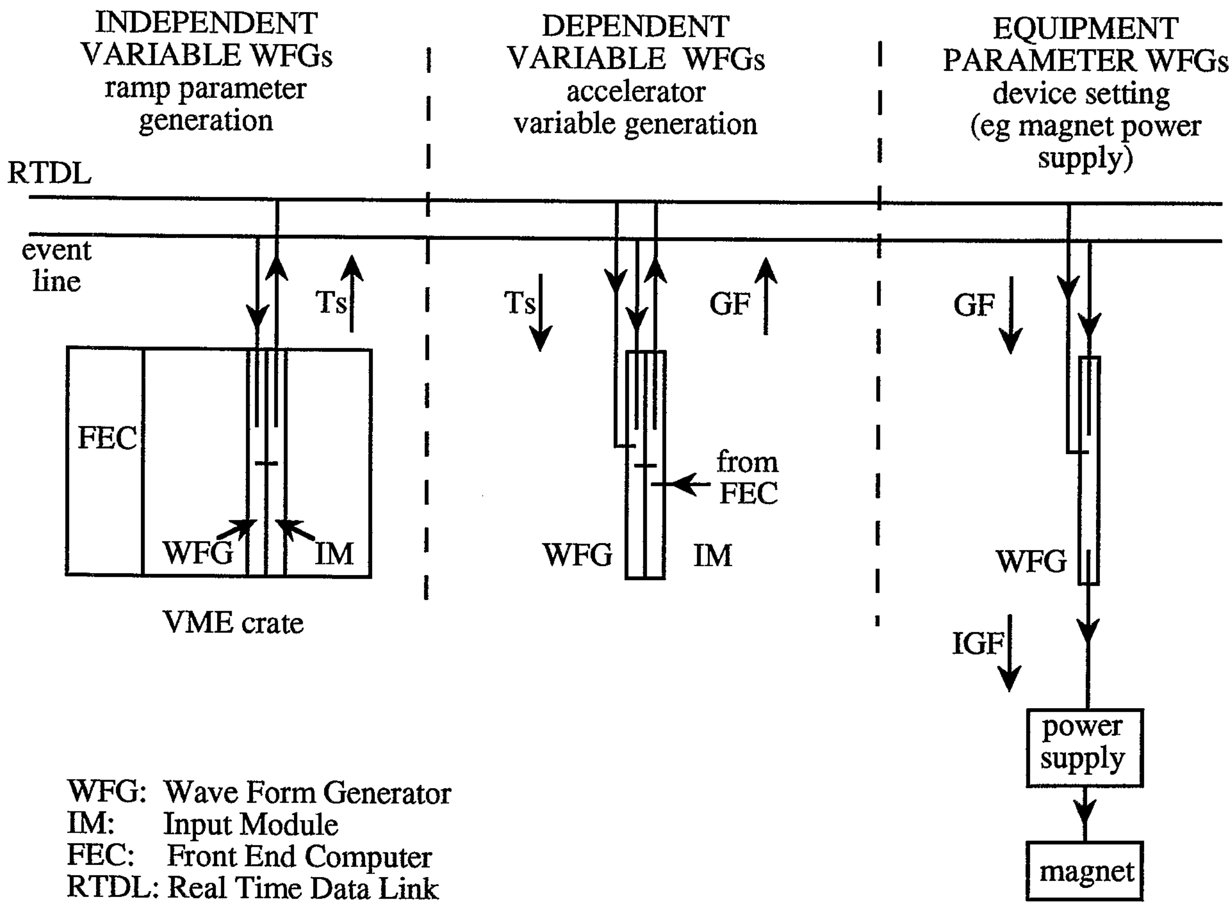

Figure 1 Conceptual relationships between INDEPENDENT variable, DEPENDENT variable, and EQUIPMENT parameter Wave Form Generators. Dependent and independent variable generators insert their output values onto the Real Time Data Link line, via RTDL Input Modules. Dependent variable and equipment WFGs read RTDL values, and modify their output values accordingly. Dependent variable WFGs may be bypassed by addressing the associated Input Module via the VME crate backplane, giving knob-like access to accelerator variables. The example shows how an arc quadrupole power supply is driven during a low beta squeeze ramp. First, the ramp parameter Ts is put onto the RTDL line as a function of time after a "start low beta squeeze" event. Next, the ramp parameter Ts is transformed into GF, the required quadrupole field gradient. Finally, an inverse transfer function is applied to find IGF, the magnet power supply current setting.

INDEPENDENT PARAMETER WFGs Ramp parameterization

The highest level WFGs always put W back onto the RTDL line, as independent time-like variables that each parameterize a single particular ramp. Obvious examples are B (main dipole field) during the energy ramp, and Ts (time after "squeeze" event) during the low beta squeeze. These values reenter the RTDL line via an Input Module (IM) card. Although Figure 1 shows both cards in the same crate for simplicity, in practice the IM cards are segregated in specialized VME crates dedicated to RTDL generation[5]. Because most of the RHIC ramps are mutually exclusive, it is probably desirable to provide the independent parameters for many RHIC ramps from a single WFG. In contrast, the energy and the transition jump ramps run concurrently, so that the transition jump ramp needs its own WFG[6].

Independent variables are generated directly by the F table, responding to a "start-ramp" event. Distinct ramps are labeled by their respective independent variables in Table 1.

Ramp name	Independent parameter	Symbol
Energy	Arc dipole field	B
Injection	Time after warning event	Ti
Transition jump	Time after warning B field	Tj
Re-bucketing	Time after re-bucketing starts	Tr
Low beta squeeze	Time after squeeze starts	Ts
Reset	Time after request for reset	T0
And more ...		

Table 1 A preliminary list of RHIC ramps, and the independent time-like variables that are put on to the RTDL line to parameterize them. These variables do not necessarily have the dimensions of time - they may be sped up, slowed down, or halted, relative to the true time.

DEPENDENT PARAMETER WFGs Accelerator variables

Intermediate level WFGs almost always insert their W values back into the RTDL line, again via an IM. They respond to an independent ramp parameter by generating a dependent variable (if a response is appropriate). Simple examples are GF and GD (field gradients of the arc quadrupoles) or SF and SD (sextupole family strengths in T/m^2). Figure 1 shows schematically how GF is generated as an RTDL variable depending on the independent variable Ts during the low beta squeeze ramp. All the dependent variables presented here have dimensions that are physical, like Tesla per meter or volts per turn, and so they may be loosely referred to as "accelerator variables".

Table 2 shows whether or not a given accelerator variable is "active" - updated at 720 Hz - during a given ramp. A given variable can only respond to one ramp at a time, despite the fact that 2 or more ramps may play simultaneously. Note, for example, that the "transition jump" ramp (Tj) plays on top of the "energy" ramp (B) without any interference. Since there is one RTDL line for Blue and Yellow rings, with a total of 255 available frames, it is important to keep the total number of dependent variables less than 128 (say). For this reason the very numerous dipole corrector and Interaction Region Quadrupole (IRQ) power supply settings are NOT reinserted onto the RTDL line.

WFG type	Variable name	Units	Active or inactive (1/0)					
			B	Ti	Ts	Tj	Tr	T0
Arc quads	GF, GD	T/m	1	1	1	0	0	1
Gamma-T quads	GGT1, GGT2	T/m	0	0	0	1	0	1
IR skew quads	GSQ1, 2, 3	T/m	1	1	1	0	0	1
Triplet skews	GTC1, 2, 3, 4	T/m	1	1	1	0	0	1
Arc sextupoles	SF, SD	T/m^2	1	1	1	0	0	1
IR octupoles	OF, OD	T/m^3	1	1	1	0	0	1
(IR decapoles)	DF, DD	T/m^4	1	1	1	0	0	1
Acc. voltage	Vacc	V	1	1	0	0	1	1
Acc. freq.	Facc	Mhz	1	1	0	0	1	1
Store voltage	Vstore	V	0	0	1	0	1	1
Store freq.	Fstore	MHz	0	0	1	0	1	1
And more								

Table 2 A preliminary list of dependent accelerator variables being placed on the RTDL line by intermediate level WFGs, and the independent ramp variables to which they respond.

Occasionally, when NO ramp is playing, dependent variables will be adjusted via the register in the associated IM, which is accessed via the VME interface through the Front End Computer. This is sketched in Figure 1. Under the control of a high level application, this gives knob-like access to accelerator variables with "real time" response at faster than 10 Hz.

EQUIPMENT PARAMETER WFGs **Magnet power supplies, et cetera**

Low level WFGs rarely put their output values back onto the RTDL line, and so have very few associated IM cards[7]. Equipment WFGs feed accelerator devices with required settings that vary as a function of an independent or a dependent variable that is read off the RTDL line. An obvious example is an arc quadrupole power supply, in which the requested current is almost linearly proportional to GF (or GD), but needs a slight correction for magnetic saturation. This correction is performed via a set of G table entries that constitute an inverse transfer function. The G table coefficient Rg is therefore GF, while the argument RG is also GF, and the G table is almost 1 in all its rows. The scale factor Sg converts to Amps. This makes the contents of the many equipment WFGs extremely simple and very static, thereby avoiding the frustrating (if rare) network problems that can occur when much data is frequently downloaded to many distributed cards. Note, however, that dipole corrector and IRQ power supply WFGs are somewhat special cases, as discussed below.

Ramp independent equipment WFGs read accelerator variables and use only the G table to perform inverse transfer function transformations. Table 3 lists all the ramp independent WFGs connected to RHIC magnets. Most of the RG arguments are listed in parentheses, to imply that the dependence of G on RG is weak, since magnetic saturation effects are usually weak[8]. The inverse transfer function transformation in a WFG will rarely, if ever, be modified. However, the flexibility to compensate for magnet to magnet differences (such as magnetic length variations) is maintained, since individual WFG transformations may be tweaked by editing the G table contents.

WFG type	Rf	Rg	RG	Rh	RH
Arc dipoles		B	(B)		
Odd length dipoles		B	(B)		
Arc quadrupoles		GF	(GF)		
Gamma-T quad families		GGT1	(GGT1)		
IR skew quads		GSQ1	(GSQ1)		
Triplet skew quads		GTC1	(GTC1)		
Arc sextupoles		SF	SF		
IR octupoles		OF	(OF)		
(IR decapoles)		DF	(DF)		
Triplet corrs (oct, dec, dodec)		B	(B)		

Table 3 A preliminary list of ramp independent equipment WFGs. The same G table plays no matter which ramp is running.

Synchronized milestones and unsynchronized corrections

The needs of the lattice designer and the accelerator operator must both be met in the generation of accelerator variables. This is achieved by having the appropriate G and the H tables read the same RTDL ramp parameter (RG = RH) and play at the same time.

For example, take the case of the low beta squeeze. Initially, the designer might create a new ramp from a sequence of 8 "milestone" lattices with beta star values of 10, 8, 6, 4, 3, 2, 1.5 and finally 1.0 meters. Each milestone defines the design strengths of arc quadrupoles, IR quadrupoles, arc sextupoles, octupoles, et cetera. The strengths of correctors such as dipole correctors and skew quadrupoles are grafted onto each milestone according to the best operational knowledge of the ring at that time. Next, the milestone values are loaded as 8 rows in the G tables of all the appropriate accelerator variable WFGs, along with 8 values of Ts, the associated time-like variable that parameterizes the ramp. For example, identically spaced Ts values of 0.0, 1.0, 2.0, 3.0, 4.0, 5.0, 6.0 and 7.0 might be selected. Finally, 8 real time values are associated with the 8 pseudo-time Ts values in the F table of the dependent WFG that generates Ts for the ramp. In practice, it is unlikely that the real time values would be identically spaced - milestones at the end of the ramp will probably be passed much more slowly than those at the beginning. The overall state transition of the ramp therefore consists of many, more minor, state transitions. At the instant that a milestone is passed, it is guaranteed that ALL WFG driven equipment will be in an explicitly defined state. The Tevatron uses this paradigm of synchronized milestones (which are called "steps" at Fermilab).

While there are real advantages in a simple definition of the full state of the accelerator at synchronized milestones, it is also highly desirable to allow for the piecemeal correction of individual subsystems at unsynchronized times. The Tevatron, where this is NOT possible, is forced into a rather fine granularity of low beta squeeze milestones by the fact that the interpolation is linear, while the variation of quadrupole bus current with beta-star has an important quadratic component. This limits the tolerances within which the betatron tunes can be held constant. The H tables are available for unsynchronized corrections in RHIC, following the AGS paradigm of independent "function" editing. Unsynchronized corrections could be used to correct for the low beta squeeze tune deviations, for example - without designing more milestones. The superposition of G and H tables is possible because the ramp is parameterized by an RTDL broadcast variable. If, instead, the ramp timing was to be generated internally in all the WFGs, then only the F table (the time table) could be used, and the G and H table interpolations could not be added.

Dipole correctors and IR Quad power supplies

The most numerous application of a WFG is to drive a dipole corrector. Since there are so many independent dipole correctors, it is neither economical nor possible to send all their excitation strengths across the RTDL as dependent variables, since WFG cards are not cheap and the RTDL line has limited capacity. Consequently, dipole corrector WFGs must respond differently to different ramps, as shown in Table 4. In some cases the H table is active to provide unsynchronized corrections on top of synchronized milestones, while in some other cases neither the G table nor the H table is active. The F time table is used when an independent closed orbit correction is applied while no ramp is running. Dipole corrector table entries are in milliradians. It is not necessary to correct for saturation effects in dipole correctors, since they are quite linear, and the requested strength values are anyway only reached by a process of successive iteration.

Ramp type	Rf	Rg	RG	Rh	RH
Energy		B	B	B	B
Injection		B	Ti		
Transition jump		B	Tj		
Re-bucketing	INACTIVE				
Low beta squeeze		B	Ts	B	Ts
Reset		B	T0		
Closed orbit correction	B				

Table 4. Activity of Dipole Corrector WFGs in response to different kinds of ramps.

Ramp type	Rf	Rg	RG	Rh	RH
Energy		B	B	B	B
Injection	INACTIVE				
Transition jump	INACTIVE				
Re-bucketing	INACTIVE				
Low beta squeeze		B	Ts	B	Ts
Reset		B	T0		
Optics correction	B				

Table 5. Activity of Interaction Region Quadrupole WFGs in response to different ramps.

Another frequent WFG application is to drive interaction region quadrupole (IRQ) power supplies. Independent setting of IRQs at each of the 6 RHIC IRs is allowed, even though the current nominal optic only distinguishes between experimental (low beta star) and other (injection beta star) interaction regions. Independent IRQ control must also be used in an optics correction role in addition to the nominal optical design role, since the IRQs cause the strongest errors in the first place! As with dipole correctors, IRQ WFGs are so numerous that they can not read dependent variables, and are also ramp dependent. IR quad table entries are in Amps. Some ramps invoke both G and H tables, for synchronized milestones and unsynchronized corrections. The calculations to compensate for magnetic saturation, and to properly model the complex power supply busing connections, are done before downloading G tables to an IRQ WFG.

Summary: the complete set of RTDL variables

Table 6 lists a (preliminary) complete set of variables that will be broadcast over the RTDL line. For every item in the list, there is one Blue and one Yellow variable (except, arguably, for some of the independent ramp parameters). There are undoubtedly items missing from this list, such as RF accelerator variables, but the table nonetheless gives a good feel for the full scope of the system.

Acknowledgements

We would like to thank Mike Harrison, Brian Oerter, and Chris Saltmarsh for their helpful comments and suggestions.

References and footnotes

1 H. Hartmann, "Specifications for the RHIC Real Time Data Link transmitter system", October 93, unpublished.

2 H. Hartmann, B. Oerter, S. Peggs, "RHIC Real Time Data Link System", to be published

3 T. Kahn, "Power Supply Waveform Generator Module Design Specification", unpublished.

4 A design choice that is still (somewhat) open is whether or not it is desirable to replace linear interpolation with quadratic or cubic interpolation.

5 One Input Module has two input channels. It is therefore possible to arrange that one IM handles one pair of independently variable Blue and Yellow RTDL parameters.

6 Another debatable design choice is whether or not to formally declare that no two ramps shall run at the same time.

7 A prominent exception is the Main Dipole Power Supply, also located in the 4 o'clock equipment building. A special arrangement between the MDPS and its WFG puts I and Idot, requested and measured, Blue and Yellow, back onto the RTDL line.

8 The main exceptions are the arc sextupoles, which saturate rather heavily.

Variable Name	Symbol	Units	Min	Max	LSB
INDEPENDENT VARIABLES					
Main dipole field	B	T	0	3.5	2.08e-7
Main dipole rate of change	Bdot	T/s	-.5	.5	5.96e-8
Injection ramp time	Ti		0	10	5.96e-7
Transition jump ramp time	Tj		0	1	5.96e-8
Re-bucketing ramp time	Tr		0	1	5.96e-8
Low beta squeeze ramp time	Ts		0	1000	5.96e-5
Reset ramp time	T0		0	1000	5.96e-5
GENERAL DEPENDENT VARIABLES					
Arc F quad gradient	GF	T/m	0	100	5.96e-6
Arc D quad gradient	GD	T/m	0	100	5.96e-6
Gamma-T quad gradient 1	GGT1	T/m	-5.0	5.0	5.96e-7
Gamma-T quad gradient 2	GGT2	T/m	-5.0	5.0	5.96e-7
CQS skew quad gradient 1	GSQ1	T/m	-5.0	5.0	5.96e-7
CQS skew quad gradient 2	GSQ2	T/m	-5.0	5.0	5.96e-7
CQS skew quad gradient 3	GSQ3	T/m	-5.0	5.0	5.96e-7
Triplet skew quad gradient 1	GTC1	T/m	-5.0	5.0	5.96e-7
Triplet skew quad gradient 2	GTC2	T/m	-5.0	5.0	5.96e-7
Triplet skew quad gradient 3	GTC3	T/m	-5.0	5.0	5.96e-7
Triplet skew quad gradient 4	GTC4	T/m	-5.0	5.0	5.96e-7
Arc F sextupole strength	SF	T/m^3	0	1500	8.94e-5
Arc D sextupole strength	SD	T/m^2	0	1500	8.94e-5
CQS F octupole strength	OF	T/m^3	-1500	1500	1.78e-4
CQS D octupole strength	OD	T/m^3	-1500	1500	1.78e-4
CQS F decapole strength	DF	T/m^4	-50000	50000	5.96e-3
CQS D decapole strength	DD	T/m^4	-50000	50000	5.96e-3
MAIN DIPOLE DEPENDENT VARIABLES					
Programmed Main Dipole Current	Ip	A	0	5500	3.27e-4
Programmed MDC rate of change	Ipdot	A/s	-775	775	9.23e-5
Measured MDC	Im	A	0	5500	3.27e-4
Measured MDC rate of change	Imdot	A/s	-775	775	9.23e-5
OTHER VARIABLES					
RF accelerator variables, et cetera ...					

Table 6 Preliminary list of all input channels to the RTDL line.