A MODEL OF THE FERMILAB COLLIDER FOR OPTIMIZATION OF PERFORMANCE

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Abstract: A Monte Carlo-type model of the Fermilab Collider has been constructed, the goal of which is to accurately represent the operation of the Collider, incorporating the aspects of the facility which affect operations in order to determine how to run optimally. In particular, downtime for the various parts of the complex are parameterized and included. Also, transfer efficiencies, emittance growths, changes in the luminosity lifetime and other effects are included and randomized in a reasonable manner.

INTRODUCTION

This model is written as a set of C++ classes, which each represent some aspect of collider operations. It is an entirely phenomenological model, with its parameters based only on direct observation of the operation of the Fermilab Tevatron Collider. Parameters in this paper are based on the period from March 1 through April 15, 1995.

A more thorough analysis of this topic can be found in the Reference.

Definition of Parameters

Many aspects of the Collider are randomized in order to realistically reflect present-day operations. The randomization comes from the C routine `srand(3V)` provided by Sun under SunOS 4.1.3. Simple correlation plots of this generator show it to be satisfactory.

The parameters used in this model are summarized in Table 1.

Stacking. Stacking is the creation and accumulation of anti-protons. The stacking rate is observed to be accurately parametrized by the following (surprising?) form:

$$R = R_0 / \cosh(S / S_c)$$

where R_0 is the zero-current stacking rate, S is the present stack size and S_c is chosen to accurately reproduce the stacking rate fall-off at higher stack values. The stacking rate is randomly reduced by upstream studies and/or other programmatic work.

Stacking downtime is parameterized as a fractional "up time" with a randomly varying time down. When in a stacking downtime, there is a probability that this downtime causes the antiproton stack to be lost. The model parameters are adjusted

Aspect	Param	Description	Units	Value	Randomize
Model	Δt	Time step in simulation	hours	0.1	-
Stacking	*D1*	Probability that stacking is okay	1/hour	0.99	-
	T 1-1	Max time stacking off	hours	10	1-10 hrs
	D2	Probability of keeping the stack	1/hour	0.4	-
	R 0	Zero-current stacking rate	mA/hour	7.5	10% less
	Sc	Critical Stacksize	mA	190	-
	Average time between lost stacks		days	8	
Accumulator	ε *pbar*	Zero-stack core emittance, normalized, 95%	mm mr	9.3 π	3 π
	g	Emittance growth per stack size	emit/mA	0.02	-
	f max	Zero-stack extraction fraction	-	0.70	0.08
	w	Extraction fraction reduction	1/mA	0.0011	-
	e all	Overall transmission efficiency (best)	-	0.8	2% per step
Main Ring	ε *p*	Initial Proton Emittance	mm mr	12 π	5 π
	N p	Initial Proton Intensity	E10/bun	25.0	1.0
Tevatron	*D3*	Probability that store is retained	1/hour	0.9801	-
	T 3-1	Max recovery time	hours	24	1-24 hours
	B	Number of bunches	-	6	-
	Fraction of stores ended intentionally		%	70	
Collider	*K*	Conv from Accelerator units to Luminosity	*complex*	4.0	20%
	τ	Initial Luminosity Lifetime	hr	11	5%
	K	Initial Lifetime growth	hr/hr	1	-

Table 1, Overview of Parameters

to accurately reflect the present operation: stacking downtime is 5 to 10%, and a stack is lost every 7 to 10 days.

Luminosity. The instantaneous luminosity is:

$$L = K \frac{N_p N_{\bar{p}}}{\varepsilon_p + \varepsilon_{\bar{p}}}$$

If the intensities are in units of E10 particles per bunch, the emittances are in units of 95% π mm mrad and the luminosity is in units of (10^{30} cm^{-2} sec^{-1}), then K is, numerically, about 4.

Each of the two intensities and two emittances above die out so that the overall luminosity obeys this form:

$$L(t) = L_0 e^{t/(\tau + K t)}$$

The lifetime growth factor K is about 1hr/hr initially. A constant growth factor does not make sense for very long stores, so the lifetime growth is a smoothly varying function which is 1.0 hr/hr at the beginning of the store and 0.5 hr/hr at 36 hours.

Downtime in the Tevatron means losing a pbar-p store. When the Tevatron is down, the amount of time down is calculated randomly from 1 to 24 hours. There is no downtime in this model greater than 24 hours. The performance of the Collider is being modelled; incorporating longer downtime would mask the optimizations which are, hopefully, being revealed. The data presented below use 30% of the stores lost by failure.

* Operated by the Universities Research Associations, Inc., under contract with the U.S. Department of Energy, contract number DE SC02 76CH03000

Scheme	Target	Best Targ Val(s)	Error bar	Exp'd Lum
Straight	Duration	21 hours	1 hour	4797 ± 24
	Stack Size	175 mA	10 mA	5054 ± 28
	Min Lum	4.5 E30	0.2	4772 ± 24
	Integrated	1100 (1/nb)	100 (1/nb)	4826 ± 30
	Stack *OR* Duration	190 mA *OR* 22 hours	n/a	5078 ± 23
Figure of Merit	Stack, Min Lum & Integrated	Stack=160 mA MinLum=6E30 Integ'd=850 (1/nb)	unknown	5141 ± 24
Ratio	Luminsoity Ratio	2.6	0.3	4988 ± 27
Difference	Luminosity Difference	10 E30	0.5 E30	5089 ± 26

Table 2, Summary of Scheme Optimizations.

Taking a Shot. We call the two-hour process of preparing the Accumulator for pbar transfers, tuning of the Main Ring and Tevatron and the transference of pbars and protons to low beta in the Tevatron a "Shot." Most of the aspects of this class are randomized. The randomizations are linear.

The average number of pbars per bunch is

$$N_{\overline{p}} = S\ (f_{\max} - wS)/B$$

where S is the stack size, $f_{\max}$ is the maximum fraction of the stack which can be extracted, w is the rate at which this fraction falls off with stack size and B is the number of bunches (6, for the present run). This is randomized by ± 8%.

The transmission efficiency of the pbars from the Accumulator to low beta is a major contributor to the performance of the collider. This transmission is randomized by small, non-unity transmissions on the way to low beta for both the the pbars and the protons.

The emittance of the pbars from the Accumulator is

$$\varepsilon_{\overline{p}} = \varepsilon_0 + gS$$

This emittance and the proton emittance are randomly grown in each of the steps to low beta.

The other randomizations are: The time necessary for shot setup is usually two hours, but 50% of the time, the shot setup is increased by up to four more hours. Also, when a store is lost, stacking stops half the time, too.

How Do We Decide When To End Stores?

The genesis of this analysis was to determine the best criteria for ending stores intentionally. We have, in the past, always ended stores by the wall clock. Three schemes for ending the stores are considered here.

Scheme 1: End when a critical parameter exceeds a target value. The parameters considered are the duration of the store, the stack size, the instantaneous luminosity and the integrated luminosity from this store. We refer to these, collectively, as the "Straight Scheme." Several variations on this scheme have been considered.

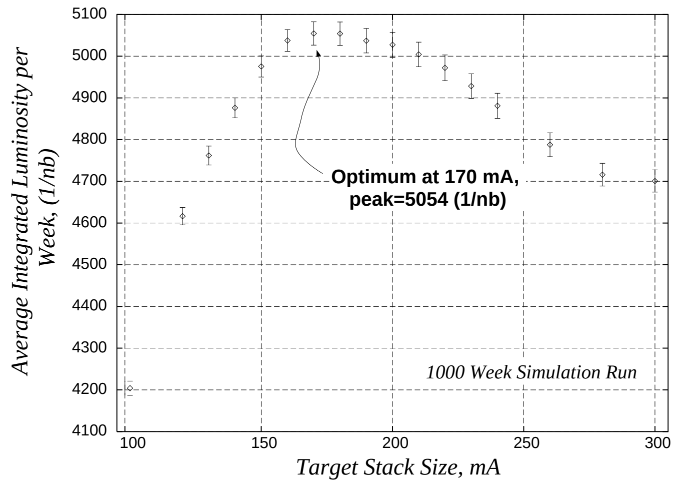

Figure 1, Optimization of the Target Stack Size.

Scheme 2: Calculate a "figure of merit" based on how some of these critical parameters exceed targets. A multiplicative factor is used to convert these (numerically) different quantities to the same basic units. The time to end the store is when the figure of merit exceeds some value, zero is used here. This is the "Figure of Merit Scheme."

Scheme 3: Assuming knowledge of the expected luminosity for a given stack size, then two approaches can be made. Calculate the ratio of the luminosity expected from the current stack size to the luminosity now; end the store when this ratio exceeds some constant. This is called the "Ratio Scheme." Or, alternatively, end when the difference between the expected luminosity and the actual luminosity exceeds some value. This is called the "Difference Scheme."

Analysis

Many analyses have been carried out with this model. They are: Which criterion is the best for ending stores; What is the character of a typical store; What is the character of a typical week; How do changes in downtime affect these results; What is the effect of improved stacking; What is the effect of other Collider improvements; How is the luminosity delivered to the experiments, that is how much luminosity is integrated at each instantaneous luminosity. Only the first three are reported here due to space limits.

Which Criterion is Best? A summary of some of the optimization results from this model is presented in Table 2. The Straight Scheme using only the Target Stack Size is the most consistent and understandable method for producing high weekly luminosities. A simple graph of average weekly luminosity for 1000 weeks of simulated running versus the target stack size is shown in Figure 1. (It has been our experience that we should shoot from stacks slightly larger than the optimum because we, as human researchers, tend to improve perfor-

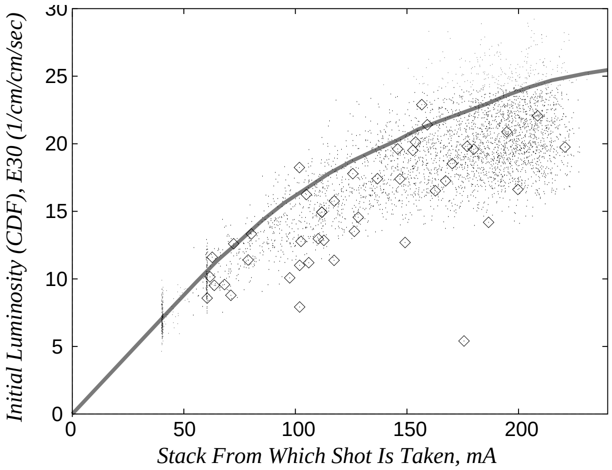

Figure 2, Initial Luminosity versus anitproton Stack Size; model predictions and actual data.

mance, unlike this model which shows the same performance at all times.) This method has the (not-to-be underestimated) benefit of being understood by all observers. Ending a store when either the stack size is bigger than 190 mA OR the store duration is more than 22 hours seems to be slightly better than the stack size criterion alone.

The figure-of-merit scheme produces average luminosities up to 3.5 sigma better than the target stack criterion alone, but many different, unrelated parameter choices give similar results. One such combination is with the following "goals" in the figure-of-merit calculation: Stack=160 mA, end luminosity=6E30, total store integrated=850 nb^{-1}. This investigation is proceeding.

The ratio and the difference schemes are each good criteria for the stable performance assumed in this model.

A definite conclusion drawn from this model is that using the store duration alone is a rather poor criterion for ending stores. The best one can do with this parameterization (21 hour stores) is 10 sigma worse than the best target stack size run. Other suggestions from the "peanut gallery" of observers have been similarly eliminated.

(It should be pointed out that the decision to end a store usually contains some sociological consideration!)

			Best Target Stack Size			Best Figure of Merit		
Aspect	**Units**		*Average*	*Median*	*Sigma*	*Average*	*Median*	*Sigma*
Stack Shot From	mA	ALL	158.2	180.9	38.1	163.1	178.3	42.9
Initial Luminosity	E30	ALL	18.64	20.52	3.93	18.83	19.99	4.09
Final Luminosity	ditto	ALL	8.00	6.55	3.48	7.81	7.75	3.50
Total Integrated	(1/nb)	ALL	650.0	695.7	245.7	681.7	734.8	263.9
Store Duration	Hours	ALL	17.0	17.8	7.6	17.7	19.6	7.4
Stack Shot From	mA	GOOD	160.6	180.2	36.0	164.7	183.9	41.8
Final Luminosity	E30	GOOD	6.74	6.22	1.85	6.38	6.24	1.57
Total Integrated	(1/nb)	GOOD	758.8	749.2	156.7	802.1	806.8	172.6
Store Duration	Hours	GOOD	20.3	17.1	5.3	21.5	19.2	3.8

Table 3, Data for a Typical Store.

Figure 2 is one which we use in Operations daily: the initial luminosity vs. stack size. The dots are from 200 weeks of this simulation, the diamonds are the real data and the line is the average of the top half of the simulation in 10 mA bins.

What is Typical? A typical store, which is ended intentionally, is characterized by the data in Table 3. Some comparison between using the Target Stack Size criterion (using 180 mA target) versus using a Figure of Merit approach can be made. Also, the difference between all stores and only those stores which are ended intentionally is shown. The sigmas are the calculated first moments of the distributions.

A typical week is characterized by the data in Table 4. Here, again, some comparison can be made between a Target Stack Size criterion and the Figure of Merit approach.

CONCLUSION

A good representation of the Fermilab Collider exists which models the operational features of the Tevatron, the Pbar Source and of shot setup. Conclusions can be made on what criteria are best for determining when to end a store. In particular, strong conclusions can be made about the unacceptability of several possible criteria. Parameters describing a typical store and a typical week can be calculated. Work on this model continues.

A nice benefit of this model has been in developing intuition on the operation of the Collider. In particular, we and the other Run Coordinators for the Fermilab Collider now have a much better idea about what to expect in day-to-day operations. Moreover, recent preformance of the real Collider has been comparable to the optimal preformance predicted here.

REFERENCE

Fermilab Technical Memo TM-1901, "Modelling the Fermilab Collider to Determine Optimal Running," E. McCrory.

		Target Stack Size			Best Figure of Merit		
Aspect	*Units*	*Average*	*Median*	*Sigma*	*Average*	*Median*	*Sigma*
Integrated Luminosity	(1/nb)	5083.1	5128.0	743.6	5140.7	5202.3	754.7
Store Hours	Hours	132.5	133.4	9.5	133.5	134.1	9.9
Integrated per Hour	(1/nb)	38.32	39.03	4.65	38.47	39.32	4.58
PBars Stacked	mA	736.6	741.1	45.3	728.6	733.6	45.6
Stacking Hours	Hours	132.8	133.9	9.1	133.8	134.3	9.3
Num Shot Setups		7.8	8	1.0	7.5	8	0.9
Hours in Shot Setup	Hours	25.12	26.05	5.37	24.0	24.8	5.1
Tevatron Downtime	Hours	8.92	8.86	5.71	8.98	9.28	5.71
Stacking Downtime	Hours	5.28	2.4	8.21	5.43	3.45	7.94
Num Lost Stores		2.58	2	1.51	2.6	2	1.5
Num Dropped Stacks		0.84	1	0.91	0.85	1	0.87

Table 4, Data for a Typical Week.