Fermi National Accelerator Laboratory

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Modelling the Fermilab Collider to Determine Optimal Running

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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.

This Memo is an outgrowth of TM-1878, which presented an entirely analytical model of the Collider. It produced a framework for developing intuition on the way in which the major components of the collider affect the luminosity, like the stacking rate and the shot set-up time, for example. However, without accurately including downtime effects, it is not possible to say with certainty that that analytical approach can produce accurate guidelines for optimizing the performance of the Collider. This is the goal of this analysis.

We first discuss the way the model is written, describing the object-oriented approach taken in C++. The parameters of the simulation are described. Then the potential criteria for ending stores are described and analyzed. Next, a typical store and a typical week are derived. Then, a final conclusion on the best end-of-store criterion is made. Finally, ideas for future analysis are presented.

1. Software framework.

This model, which is called `simulate_week`, is written as a set of C++ classes, each of which portrays some aspect of collider operations. The basic goal of this model is to accurately reflect the real Tevatron Collider at many levels—get the right initial luminosity vs. stacksize, pbar transmission from Accumulator to low-beta, stacking downtime, etc. A period of very nice running from July 23 through Aug 21, 1994 is the basis of the parameters for this model—this is referred to as the "magic period."

`simulate_week` is a Monte Carlo model, randomizing many aspects of the Collider, and stepping through time in small increments. The increment chosen here is 0.1 hours, 6 minutes. The randomization comes from the C routine `srand(3V)` provided by Sun under SunOS 4.1.3 (a.k.a., Solaris 1.1). The only test performed on this random number generator to date is to plot `srand(seed)` vs `srand(seed)` on consecutive calls. The results, for 100000 calls, 50000 pairs, are shown in Figure 1. A simple check is performed by looking at the density of points as a function of distance from the center of this plot, Figure 2. The data are shown with the expected uniform

Aspect	Param	Description	Units	Typical Value
Stacking	D1	Downtime probability for stacking to be off	1/hour	0.99
	T 1-1	Max time stacking off	hours	10
	D2	Probability of dropping stack	1/occurance	0.4
	R 0	Zero-current stacking rate	mA/hour	5
	Sc	Critical Stacksize	mA	150
Main Ring	E-C	Coalescing efficiency	-	0.7
	w	Coalescing falloff per stacksize	1/mA	.00195
Tevatron	D3	Downtime probability for loosing a store	1/hour	0.97
	T 3-1	Max recovery time	hours	6
	B	Number of bunches		6
Collider	g	Emittance growth per stack size	emit/mA	0.073
	K beta*	Conversion from accelerator units to luminosity	*	6.4
	S0	Target Stack size	mA	*
	T0	Maximum Store Duration	hours	*
	Lmin	Minimum acceptible Luminosity	E30/cm/cm/sec	*
	I	Target Integrated Luminosity	(1/nb)	*
	S1	Minimum acceptible Stacksize	mA	80

Table 1. Parameters for Modelling the Fermilab Collider. Asterix (*) indicates that explainations in the text are necessary.

density. It is generally acknowledged that the problem with most simple random number generators is at the corners. Figure 3 shows a blow-up of the largest area, and, in fact, there is a small reduction in the density at the edge. This random number generator should be adequate.

A list of some of the parameters used in this analysis is presented in Table 1.

1.1. Class Stack.

This class is intended to represent the operation of the stack. The size of the stack is returned as `double(stack_instance)`; time is stepped through `stack_instance.step_time(delta_time)`; stack is removed, as during shot setup, through `stack_instance.remove(factor)`. A few other methods are included for gathering statistics. All of the details of how a "stack" behaves are hidden in these methods.

The stacking rate is assumed to be

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

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. Operationally accurate values for these parameters are R_0=5.0 mA/hour and S_c=150 mA. This is the form used for the devices `A:EXPSR` and `A:SREFF`. In practice, aside from downtime, the stacking rate is reduced by Main Ring studies, Booster studies and/or NTF. The effect of these is (more or less) random. The model randomly reduces this rate linearly by up to 50%, 40% of the time, for an average reduction of 5%. This also accounts for very short, unreported Linac, Booster or MR downtimes.

The probability of stacking downtime, which, of course, includes the downtimes for Linac, Booster, Main Ring, Debuncher and their associated transfer lines, is given by the parameter D1. At each step in time, a random number is generated and compared to D1. If that random number is greater than D1, then stacking is down. Then, a down time, T_{1-1}, is calculated as 0 to 0.8 hours, 80% of the time, and as 0.8 to 10 hours 20% of the time, for an average downtime of about 1.4 hours. When a "downtime" is dictated, there is a probability, D2, that this is actually an Accumulator downtime, rather than just a stacking downtime, and the stack is lost. If the stack is lost, it takes from 0 to 8 hours to recover and resume stacking.

In the Collider today, the stacking downtime is 5 to 10%, and a stack is lost every 7 to 10 days. The data presented below use D1 and D2 that are adjusted for 8.5% downtime and one stack lost every 9 days. With the randomization on the down time stated here, D1=0.99 and D2=0.5 are used.

A plot of the stacking rate as a function of stack size for 4 weeks of running is presented in Figure 4a, to be compared with 4b, the actual data from August, 1994 (courtesy E. Harms). A histogram of the stacking rate between 100 and 110 mA is shown in Figure 4c (50 weeks overall). The simulated profile is not entirely realistic, but it seems likely that modifying this distribution will not greatly enhance the validity of the model.

1.2 Class Luminosity.

As with class Stack, the details of how a "Luminosity" works are hidden in the methods. The major methods are: `double(lum_instance)` returns the luminosity now, in units of E30 $cm^{-2}sec^{-1}$; `lum_instance.step_time(double)`; `lum_instance.drop()` removes the store (intentionally); `lum_instance.integ()` returns the integrated luminosity for this store so far.

The instantaneous luminosity is calculated to be:

$$\mathcal{L} = K \frac{N_p N_{\bar{p}}}{(\epsilon_p + \epsilon_{\bar{p}})}$$

where the intensities are in units of E10 particles, the emittances are, nominally, vertical and in units of 95% π mm mrad. For the "magic period," K was between 4 and 7, see Figure 5. A constant value of 6.3 is chosen for this model, representing the high side of this value from the data.

The luminosity dies out according to the standard form:

$$\mathcal{L}(t) = \mathcal{L}_0 e^{t/(\tau+Kt)}$$

where the growth factor K is about 1hr/hr. A constant growth factor does not make sense for very long stores, so the following form has been assumed:

$$K = \frac{C}{\sqrt{1+(C+t)^2}} + \frac{Ct^2}{\left(1+(C+t)^2\right)^{1.5}}$$

This form is the derivative of 1/sqrt(X). C is about 20. This means that the lifetime growth is 1.0 hr/hr at the beginning of the store and about 0.5 hr/hr at 36 hours.

Downtime in the Tevatron means losing a store. That probability is D3 in the model. When the Tevatron is down, according to the comparison of D3 with a random number, the amount of time down, $T_{3\text{-}1}$, is calculated randomly from 1 to 24 hours: linearly from 1 to 5 hours 80% of the time, and from 5 to 24 hours the remaining 20% of the time.

It is not necessary to consider in this model, for example, a Tevatron quench which leads to a magnet replacement and many days off. For the sake of calculations from this model, it is only necessary to consider that the store is lost and that there is some recovery time, during which stacking can usually proceed. We are modelling the performance of the Collider; incorporating downtime longer than about a day would take this model into the realm of representing the operation of the facility, and probably mask the optimizations which are, hopefully, being revealed.

The data presented below use one store lost out of three, the observed operational value, which corresponds to D3=0.967.

1.3 Class Shot.

There is a lot of randomization in this class. Most of the randomizations are a multiplicative factor calculated as:

$$f = \text{range}\,(0.5 - \text{ran})$$

where ran is a random number between 0 and 1 with, as appropriate, extra limits imposed on the answer (e.g., transmission ≤ 1.0).

The number of pbars extracted from the stack 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 (observed to be 0.78), w is the rate at which this fraction falls off with stack size (0.00195 [1/mA]) and B is the number of bunches (6, these days). This is randomized by $\pm 5\%$. Figure 6 shows data from the "magic period" for the fraction of the stack removed, from which this relationship is obtained.

The percent of the stack which is extracted is a function of the stack size and of the longitudinal area of the RF which is applied to the stack to perform the extraction. For the "magic period," a value of 1.25 eV-sec was used. Other values that have been used for routine operation have been 0.8 and 1.05 eV-sec. This model is adjusted to represent extractions with 1.25 eV-sec buckets.

The emittance of the pbars from the Accumulator is

$$\epsilon_{\overline{p}} = \epsilon_0 + g\,S$$

where the minimum emittance is 6 π and g, the emittance growth rate as a function of stack size, is 0.073 π/mA. There is no randomization.. Figure 7 shows the pbar vertical emittance vs. stack size, from which this relationship is obtained.

The transmission efficiency to low beta vs stack size is measured during the "magic period" and shown in Figure 8a. It is broken down in the model so that the coalescing efficiency is the bulk of this. The coalescing efficiency is taken as:

$$e_{\text{coal}} = e_{\text{coal}_0} - 0.0004(S - S_n)$$

where S_n is the stack size at which the coalescing starts to fall off, 80 mA. The multiplicative randomization here is gaussian

$$0.1\left(1 - e^{-(\text{ran}-1)^2/0.2}\right)$$

100 weeks of running produces the efficiency vs. stack size presented in Figure 8b, with the data from the "magic period." Figure 8c is a histogram of the coalescing efficiency for shots in the model at 140 mA.

Figure 9 shows the major plot of this simulation: Initial luminosity vs. stack size. It has become customary for this to be shown at the Nine O'clock meeting each day. This Figure also presents data from the August "magic period" for comparison. It is generated with a Target Stack Size=160, see below for explanation. Some of the parameters in class Shot have been adjusted to accurately reproduce this relationship.

1.4 Other Randomizations.

There are other randomizations which do not readily fall under one of those classes. The time allotted for shot setup is usually two hours, but 50% of the time, the shot setup is increased by up to 4 more hours. Also, when a store is lost, stacking stops half the time, too.

2. How Do We Decide When To End Stores?

The basic question asked by this analysis is "What is (are) the best criterion (criteria) for ending stores?" It is the goal of this model to include all the mitigating circumstances accurately enough to be able to believe that the best set of criteria in the model will be the best in reality. For example, one specific debate is whether we should have huge stacks so that when we lose a store we can still get a good shot off from the remaining pbars. Conversely, some would say that we need to use the pbars as quickly as possible so that when we lose a stack, we have a good store in.

Five schemes for ending the stores are considered here.

Scheme 1: End when a critical parameter exceeds a target value. Specifically, end the store when this statement is true:

```
Stack Size > Min Stack Size AND
     Luminosity == 0 OR
     Store Duration > Max Duration OR
     Luminosity < Min Luminosity OR
     Stack Size > Target Stack Size OR
     Store Integrated Lum > Target Integrated Lum
```

This is the "Straight Scheme."

The manner in which we normally operate is to do a shot at some small stack size (usually 40 mA), then stack to the Min Stack Size (usually 80 mA), then stack to the Target Stack Size. Although this logic is not shown here, it is included in this and all the other schemes.

Scheme 2: Same as 1 except two of the last four portions of the boolean formula must hold. This is the "Vote Scheme."

Scheme 3: Calculate a "figure of merit" based on how much each of the portions exceeds the target:

```
figure_of_merit = 0.125×(stack_size - Target Stack Size) +
                  -3.333×(instantaneous_lum - Min Luminosity) +
                  0.025×(integ_lum - Target Integrated)
```

These factors are chosen somewhat arbitrarily. "1 merit point" is assigned for every 8 mA above the Target Stack Size, 1 point for every 0.3 E30 ($cm^{-2}\,sec^{-1}$) below Min Luminosity and 1 point for every 40 nb^{-1} above the Target Integrated Luminosity. These multipliers are based only on my own personal experience on the relative relevance of these quantities. Note that there is no restriction that this figure of merit be positive: it is negative, for example, when a store goes in. The time to end the store is when `figure_of_merit` exceeds the user-supplied target for this quantity. This is the "Figure of Merit Scheme."

Scheme 4: Calculate the ratio of the luminosity expected from the stack size now to the luminosity now; end the store when this ratio exceeds some constant, like 2.71828, for example. This is called the "Ratio Scheme."

Scheme 5: Like the Ratio Scheme, but cut when the difference between the expected luminosity and the actual luminosity exceeds some value. This is called the "Difference Scheme."

End On	Best	Integrated	Sigma
Stack Size	120 mA	3251 (1/nb)	15.9
Duration	23 hours	3258	15.1
Min Luminosity	3.5 E30	3231	15.4
Integrated	550 (1/nb)	3191	15.9

Table 2. Optimization Results from the Straight Scheme.

3. Which Criterion/Criteria To Use?

This question cannot be answered authoritatively without an extraordinarily complex scheme, probably using a scheme which has not been invented. But a complicated scheme cannot work in reality since everyone would complain too much. So let's look at the schemes proposed here.

3.1 Using the Straight Scheme.

For the basic parameters outlined above, it is possible to calculate the best criterion, using the Straight Scheme for ending stores. In this analysis, only one parameter is allowed to be used for the cut. For example, when the Store Duration portion is intended to end the store, the other three limits are set to fairly unrestrictive values, for example, Min Luminosity: 1.0, Target Stack Size=200, Target Integrated=1000. These results are summarized in Table 2. The results are displayed in Figure 10 (a-d). With this parameterization, using the Straight Scheme, using only the stack size or the store duration are equivalent. The other two criteria are slightly inferior. We should be able to average 3251 nb^{-1} per week with a target stack size of 120 mA.

Let's look in detail at exactly what it means to cut *only* on, say, the target stack size. With Target Stack Size=120, then we usually end the store when the stack reaches 120 mA. The exceptions are, of course, (a) when the store drops out early (put another one in asap), and (b) when we lose the stack while a store is in. In the latter situation, we may have to solve the problem in the Accumulator (the down time for this downtime), re-establish stacking, and then, finally, kill the store when we get to 40 mA. This could mean that the store stays in for 14 hours longer than a normal store (6 hours for the downtime plus 8 hours to stack to 40 mA). This, in fact, may not be very realistic, since we would probably allow an access to MR in this situation.

Another exception would be if the store drops out unexpectedly just before we were going to end it anyway, but we continue stacking. Here, we could be stacking for many hours while we "solve" the problem that caused the store to drop out. We would then shoot from a stack bigger than the Target Stack Size.

What about combining two criteria, for example, Target Stack Size=120 and Min Luminosity=4.5? This has been explored:

```
Target Stack Size = 120, 130, 140, 150 mA; with
Min Luminosity = 3, 3.5, 4, 4.5 5 E30.
```

Table 3 presents the best 20 choices on this grid. Note that the store would be ended when either the stack size exceeds, for example, 130 mA *or* the luminosity falls below 3.0E30, a completely independent test. This aspect of this scheme is somewhat more difficult to optimize, given its multi-dimensional nature. But it seems that some improvement can be had here. Perhaps this model could be put under the control of a complex, multi-dimensional fitting algorithm (like MINUIT) to search this parameter space for the best set of criteria.

One of these must be true:		Weekly averages for 1000 weeks	
Stack >	Lum <	Integrated	Sigma
130 mA	3.0 E30	3262.26 (1/nb)	15.622
130	3.5	3261.39	15.8611
140	3.0	3260.74	15.8916
150	3.5	3260.06	15.1966
140	3.5	3257.43	15.639
120	3.0	3253.47	15.8171
150	3.0	3247.2	15.4574
120	3.5	3244.09	15.6214
130	4.0	3243.64	15.869
120	4.0	3235.79	15.4682
140	4.0	3230.27	15.4935
150	4.0	3229.5	15.5426
140	4.5	3217.04	16.2387
150	4.5	3215.03	15.7876
130	4.5	3211.26	15.7102
120	4.5	3208.23	15.6289
140	5.0	3114.52	16.2034
150	5.0	3112.56	16.4317
120	5.0	3108.84	15.9156
130	5.0	3097.54	16.5273

Table 3. Best tries from the Straight Scheme, allowing more than one criterion to win.

2 of 3 of these must be true:			Weekly averages for 1000 weeks	
Stack >	Lum <	Integ'd >	Integrated	Sigma
100 mA	3.75 E30	550 (1/nb)	3240.61 (1/nb)	15.6188
100	4.25	550	3235.48	15.8815
130	3.5	500	3235.38	16.8618
100	3.5	550	3234.22	15.7927
120	4	550	3234.06	16.2439
120	3.75	550	3234.04	16.3482
100	4	550	3233.53	16.1814
110	4	550	3232.35	16.063
130	3.75	500	3231.5	16.6605
110	3.75	550	3230.89	16.1464
120	3.5	450	3230.44	15.981
120	3.5	550	3228.81	16.1725
140	3.75	450	3228.64	17.0282
100	3.5	500	3227.58	15.5702
130	3.75	550	3227.13	16.1136
130	3.5	450	3226.09	16.7868
120	3.5	400	3225.12	16.363
120	3.75	500	3224.91	16.1778
130	3.5	400	3224.47	17.1313
140	4	500	3224.16	17.2918

Table 4. Best choices from the Vote Scheme.

3.2 Using the Vote Scheme.

Using the basic parameters described above, a grid search over a reasonable range of Target Stack Size, Min Luminosity and Target Integrated has been conducted. The store is ended if two of the three tests succeed. The grid is:

```
Target Stack Size = 100, 110, 120, 130, 140 mA
Minimum Luminosity = 3.5, 3.75, 4, 4.25, 4.5 E30
Target Integrated = 400, 450, 500, 500 (1/nb).
```

The best twenty combinations of these for a 1000 week simulation are presented in Table 4. A strong conclusion cannot be made on which combination of criteria is best. It seems possible that this analysis is confused by the fact that these three criteria are not independent or completely orthogonal. The best choice, Target Stack=100 mA, Min Luminosity=3.75 E30 and Target Integrated=550 nb^{-1}, gives an average slightly worse than the best Straight Scheme.

3.3 Using the Figure of Merit Scheme.

Intellectually, it would seem that this scheme would be the most likely to produce the best luminosities. In fact, this is basically what the Run Coordinator often does to decide when to end a store. However, it is difficult to accurately parameterize and optimize this scheme. As with the pervious tables, a grid of parameters is explored to see if anything stands out. The grid is:

```
Target Stack Size = 80, 90, 100, 110 mA
Minimum Luminosity = 3.5, 4, 4.5, 5.0 E30
Target Integrated Luminosity = 400, 450, 500, 550 (1/nb)
Figure of Merit = 2, 3, 4, 5.
```

Figure of Merit.	Collider Target Values			Averaged over 1000 Weeks	
	Stack	Lum.	Integ Lum	Integrated	Sigma
4.0	90 mA	5 E30	500 (1/nb)	3293.4 (1/nb)	15.6718
4.0	80	5	550	3293.4	15.6718
4.0	110	5	400	3293.4	15.6718
4.0	100	5	450	3293.4	15.6718
2.0	90	4	500	3292.99	15.7846
2.0	80	4	550	3292.99	15.7846
2.0	110	4	400	3292.99	15.7846
2.0	100	4	450	3292.99	15.7846
3.0	80	3.5	400	3291.49	15.647
2.0	120	5	450	3290.34	15.6829
2.0	110	5	500	3290.34	15.6829
2.0	100	5	550	3290.34	15.6829
2.0	90	3.5	400	3288.12	15.615
2.0	80	3.5	450	3288.12	15.615
4.0	90	4.5	450	3287.59	15.5292
4.0	80	4.5	500	3287.59	15.5292
4.0	100	4.5	400	3287.59	15.5292
4.0	90	4	400	3287.17	15.2757
4.0	80	4	450	3287.17	15.2757
4.0	80	3.5	400	3284.36	15.516
5.0	80	3.5	400	3283.77	15.8245
4.0	90	4.5	500	3283.68	16.0613
4.0	80	4.5	550	3283.68	16.0613
4.0	110	4.5	400	3283.68	16.0613
4.0	100	4.5	450	3283.68	16.0613

Figure of Merit	Collider Target Values			Averaged over 1000 Weeks	
	Stack	Min Lum	Integ Lum	Integrated	Sigma
2.0	90	3.5	500	3283.47	15.6276
2.0	80	3.5	550	3283.47	15.6276
2.0	110	3.5	400	3283.47	15.6276
2.0	100	3.5	450	3283.47	15.6276
3.0	120	4.5	450	3283.37	15.7257
3.0	110	4.5	500	3283.37	15.7257
3.0	100	4.5	550	3283.37	15.7257
5.0	90	5	500	3282.99	15.228
5.0	80	5	550	3282.99	15.228
5.0	110	5	400	3282.99	15.228
5.0	100	5	450	3282.99	15.228
3.0	90	4.5	500	3282.4	15.4932
3.0	80	4.5	550	3282.4	15.4932
3.0	110	4.5	400	3282.4	15.4932
3.0	100	4.5	450	3282.4	15.4932
5.0	90	3.5	400	3281.74	15.6657
5.0	80	3.5	450	3281.74	15.6657
4.0	120	4.5	450	3281.41	15.764
4.0	110	4.5	500	3281.41	15.764
4.0	100	4.5	550	3281.41	15.764
2.0	90	4.5	500	3280.83	15.4406
2.0	80	4.5	550	3280.83	15.4406
2.0	110	4.5	400	3280.83	15.4406
2.0	100	4.5	450	3280.83	15.4406
5.0	80	4	400	3279.79	15.402

Table 5, Exploring the Figure of Merit Scheme, representing the best 50 average weekly integrated luminosities in the grid.

Scheme	Best Target	Ave Lum	Sigma
Ratio	2.9	3263.63 (1/nb)	15.34
Difference	9 E30	3284.0	15.26

Table 6, Summary of the Ratio and Difference Schemes.

Of the 256 points on this 4-D grid, the best 50 are shown in Table 5. This method appears to be better than the other schemes. However, it also shows the frustration with using this scheme–many different criteria produce similar or identical results. There are too many parameters for this simple analysis to produce a clear winner.

3.4 Using the Ratio and Difference Schemes. These results are summarized in Table 6. Either one of these schemes would do very nicely as the only scheme one would follow for ending stores. The peak is comparable to the best of any of the other schemes, and a little bit better than any of the straight schemes.

3.5 Conclusions on the Best Scheme. It is difficult to say precisely what scheme is the best in the real collider since the actual scheme often is based on sociology, that is: what time of day is it? Would this shot setup span a shift change? Would this shot setup be at the pre-dawn hours on a weekend when the operations staff is the least alert? Is John Doe going away for a month, so we must get in as many shots as we can while he is here? Is the Director watching? (etc...)

Having said that, this analysis shows that for this model, the straight scheme using a **target stacksize of 120 mA**, or using a **store duration of 23 hours** would do just fine. The best scheme seems to be the Difference scheme and a **difference of 9E30**, since this is fairly simple to understand

and to implement. The ratio scheme with a **ratio of 2.9** is very good, too. Applying the straight scheme using two criteria (130 mA OR 3.0 E30) is also good. **The figure-of-merit scheme** seems to give numbers better than the best of the other schemes, but at the significant expense of a general understanding of the process.

It is also reasonable to explore which of these schemes is least dependent on the parametrization chosen here, that is, if the stacking rate were to change, or if the downtime were different, etc. Section 4 deals with this.

3.6 Editorialization. The best scheme, which cannot be coded, is to live as a run coordinator, faced with the moment-to-moment responsibility of determining when to end the stores. In this situation, one looks at all of these criteria and uses one's gut to decide! For example, it has been my experience that when we shoot from 100 mA stacks all the time, we learn how to shoot from 100 mA stacks very well. If we sit at a much higher value, say 140 mA, then it is very likely that we will learn how to shoot there better than this model would predict. I recommend that the run coordinator look at all of these criteria, especially the target stack size, the ratio and the difference schemes, and push to slightly higher stacks always. I believe that with enough experience, we will learn how to make the luminosity-vs-stack-size graph not roll off so badly as it does now.

4. Varying Other Parameters

It is important to see the effect of varying these parameters on the results of the analysis. First we consider the "Minimum Stack Size" parameter. Figure 11 shows the integrated luminosity per week for 1000 weeks of running when the minimum acceptable stack size is the varying parameter. In other words, the minimum stack size we can shoot from in all situations except when we are recovering from a lost stack. The straight scheme with a target stack size of 125 mA is used. Notice that there is not much difference among the choices. Any choice below about 80 mA is satisfactory. Using the target stack size or the ratio schemes doesn't matter.

Now I address the question of the stability of the various schemes. That is, which choice of scheme is least dependent on these parameterizations. First I ask: What is the effect of the lifetime on this model? The previous data have been assuming an initial lifetime of 12 hours. Table 7 shows the results for various combinations of lifetime and lifetime growth for the three prominent Schemes. A growth factor of 0.5 means that the lifetime grow at half the nominal rate, for a worse overall lifetime at the end of the store. The error bar on the optimal choice is an estimate of the uncertainty of this optimum, based on the size of the luminosity error bar and the values obtained from adjacent values. It appears that the Difference Scheme is the most stable, and it is generally the best absolute choice.

Finally, Table 8 shows the optimization for the three easy schemes using various stacking

			T=10, G=1	T=12, G=1	T=11, G=0.5	T=11, G=1.5
Target Stack Size	*Best*	*mA*	115 ± 20	120 -5 +20	110 ±10	130 ±7
	Ave Lum	*1/nb*	3045.8 ± 15.4	3251.9 ±15.8	2967.3 ± 13.8	3331.39 ±16.3
Ratio Scheme	*Best*		3.1 ± 0.1	2.9 ± 0.3	3.2 ±0.3	2.9 ± 0.05
	Ave Lum	*1/nb*	3078.0 ±13.9	3268.1 ±15.4	3065.4 ±14.2	3348.7 ±14.8
Difference Scheme	*Best*	*E30*	9 ± 0.3	9 ±1	9 ±0.3	9 ±0.5
	Ave Lum	*1/nb*	3088.5 ± 14.4	3284.0 ±15.3	2983.1 ±13.7	3364.7 ±15.5

Table 7, Effect on optimizations from varying the lifetime parameterization; T is the initial lifetime of the store, and G is the lifetime growth factor, see text.

Optimization Scheme			Stacking Rate 4 mA/hr	5 mA/hr	6 mA/hr	10 mA/hr
Target Stack Size	*Best*	*mA*	110 +20 -5	120 +20 -5	130 +- 10	150 +- 10
	Ave Lum	*1/nb*	2959.6 +- 15.7	3251.9 +- 15.9	3467.8 +- 15.5	3910.0 +- 13.8
Ratio	*Best*		3.4 +- 0.2	2.9 +0.4 -0.1	2.6 +0.3 -0.05	2.1 +- 0.2
	Ave Lum	*1/nb*	2983.1 +- 15.6	3263.6 +- 15.3	3491.4 +- 14.3	3909.2 +- 14.1
Difference	*Best*	*E30*	9 +- 1	9 +- 1	8.5 +- 1	7 +- 0.5
	Ave Lum	*1/nb*	2990.7 +- 16.0	3284.0 +- 15.3	3498.0 +- 14.8	3933.6 +- 13.8

Table 8, Comparison of the optimizations for the three simple schemes for different stacking rates.

rates. Again, the Difference Scheme is the least sensitive to this variation in the parameters, and it gives very good results.

The conclusion here is that the Difference Scheme is the least sensitive to the choice of Collider parameters of the three Schemes analyzed. It is also the best overall scheme.

5. What is Typical?

This section displays data from the model to describe what a typical store and what a typical week would look like. These numbers can be used to assess the performance of the real Collider. The figures presented here are for the Straight Scheme and a Target Stack Size of 120 mA.

A typical store, which is ended intentionally, is best determined from studying Figure 12. Initial and final luminosities; Integrated luminosity for one store; Store duration; Stack Size. It can be seen that these distributions are not gaussian, but almost laplacian in that there seems in each case to be an upper limit for each. Table 9 presents the calculable numbers for these graphs: mean, median and sigma for the three major "simple" schemes. Note that Figure 12c shows the store duration

Quanitity		Difference	Ratio	Target
L0	*Mean*	11.81	11.92	12.28
	Median	10.84	12.39	13.72
	Sigma	1.78	2.10	2.15
L Final	*Mean*	4.78	4.38	4.62
	Median	4.80	4.40	5.29
	Sigma	0.67	0.47	1.21
Integrated Luminosity	*Mean*	458.6	495.9	542.8
	Median	450.4	498.5	538.0
	Sigma	107.4	150.4	80.9
Store Duration	*Mean*	17.57	19.69	21.46
	Median	15.7	19.7	18.4
	Sigma	4.20	4.86	5.38
Stack Size	*Mean*	95.00	100.72	106.86
	Median	95.51	98.53	126.16
	Sigma	22.75	31.85	29.35

Table 9, Calculable numbers for a "typical" store.

Measured Quantity	Units	Mean	Median	Sigma	*Target*
Delivered Luminosity	1/nb	3284.0	3325.5	482.7	*3566.9*
Pbars Stacked	E10	501.2	504.8	32.0	*520.8*
Time in Store	hours	122.9	123.6	13.6	*130.4*
Time Stacking	hours	130.5	132.3	9.7	*137.2*
Setup time	hours	25.1	25.1	5.7	*22.3*
# of stores	-	7.8	8.	1.16	*8.*

Table 10, Calculable numbers for a "typicial" week. The *Target* is the median plus one-half sigma.

histogrammed for both intentionally-ended stores and stores which ended on a failure. This agrees, qualitatively, with data from the "magic period."

Now it is possible to understand everything in Figure 9, Initial luminosity vs. stack size. It is for 1000 weeks of running. In order to see effects out to larger stack sizes, the straight scheme is used with the Target Stack Size=160 mA, Min Luminosity=2 E30, Target Integrated Luminosity=1000 nb^{-1} and Store Duration=48 hours. A line is drawn through the data to depict the average functional value.

What is a typical week? The parameters that most of us care about for a week include the integrated luminosity delivered (nb^{-1}), number of pbars stacked (mA), store hours and stacking hours. These quantities are histogrammed for the 1000 weeks in Figure 13. Table 10 presents the calculable parameters for these quantities for the 1000 weeks using the Difference Scheme: mean, median, sigma and something which shall be called a "target." A "target" is a non-changing goal for this parameter which is determined through reasonable expectations, but is a little optimistic. It should be better than both the average and the median, but not statistically different. A choice of 0.5*sigma better than the median seems reasonable, and is how this column is calculated.

6. Analysis of Reliability.

It is possible to use this model to analyze the effect of better or worse reliabilities on the performance of the Collider. What would happen if fewer stacks were lost? More? What about fewer or more stores lost? Figure 14 shows five effects, using the straight scheme with "Target Stack Size" as the variable parameter: Normal reliability, Tevatron three-times more reliable (that is, 3X fewer stores lost), the PBar source three-times more reliable (stacking downtime 3X smaller AND stacks lost 3X less frequently), PBar 2X worse and Tev 2X worse (the "bad-old days").

Table 11 presents these numbers for the three prominent Schemes. In this case, the Ratio and Difference Schemes are equally insensitive to the variations in the downtimes.

The results are intuitive, except, possibly, for the fact that Tevatron downtime has a bigger effect than PBar downtime. This is understood in the following context: When a store is lost, one has lost about half of the expected luminosity: 200 nb^{-1}, and the next store's initial luminosity is diminished by a little bit, say, 50 nb^{-1}. (Because we will be shooting from a slightly smaller stack, it will take longer to stack up to 120, so the next store will stay in longer at lower luminosity.) Averaged over a week when, on average, 2.3 stores are lost, yields about 575 nb^{-1}/week due to Tevatron downtime. When a stack is lost, the store stays in until 40 mA is achieved, integrating luminosity all the way. In this parameterization, the luminosity lifetime continues to grow forever, so a lot of luminosity can be integrated! The next two stores are down by about one-third, and about 300 nb^{-1} are lost while we stack up to 40 mA. So the overall effect is about 0.3*450 + 300 = 525 nb-1. But this only happens 0.7

			TeV 3X Better	PBar 3X Better	TeV 2X Worse	PBar 2X Worse
Target Stack Size	*Best*	*mA*	120 ± 10	140 ± 10	130 +20 -10	120 ± 7
	Ave Lum	*1/nb*	3740.8 ± 13.6	3464.1 ± 14.2	2765.3 ± 17.0	2972.8 ± 17.7
Ratio	*Best*		2.7 ± 0.1	2.8 +0.4 -0.1	2.9 ± 0.2	2.9 ± 0.1
	Ave Lum	*1/nb*	3760.0 ± 13.0	3480.6 ± 14.2	2773.9 ± 17.2	2997.1 ± 17.3
Difference	*Best*	*E30*	8 ± 0.5	9 ± 0.3	9 ± 0.8	9 ± 0.5
	Ave Lum	*1/nb*	3784.2 ± 13.0	3490 ± 13.5	2784.5 ± 17.2	3003.2 ± 17.8

Table 11, Analysis of the various schemes, varying the parameterization of the reliability of the accelerators.

			Expected Luminosity Curve	
Scheme			-20%	+20%
Taget Stack Size	*Best*	*mA*	120 +20 -5	120 +- 20
	Int Lum	*1/nb*	2595.0 +- 12.7	4032 +- 19.6
Ratio	*Best*		> 3.2	< 2.4
	Int Lum	*1/nb*	> 2580	> 4070
Difference	*Best*	*E30*	10 +- 0.5	7 +2 -1
	Int Lum	*1/nb*	2626.1 +- 12.1	4099 +- 18.9

Table 12, Effect on the optimizations for different Expected Luminosity Curves.

times per week, so the impact is 370 nb^{-1}/week.

7. Is the Difference Scheme really the best?

The one remaining question on the viability of the Difference Scheme is to determine the effect of having the predicted "Lum vs. Stack Size" function wrong. In particular, if we are consistently below this line (or above it), is this still the best scheme? Table 12 presents the results from having the actual luminosity fall 20% above or below the expected curve. Not too surprisingly, the Difference Scheme is affected by this change, by exactly the amount of the degradation. However, the Ratio Scheme is affected also. The Target Stack Size Scheme is okay. Thus, it seems that the Difference Scheme is still the best choice.

8. Modelling Future Improvements.

This model is useful in predicting the real-world effect of improvements in the Collider. One, presented here, is the effect of improving Main Ring coalescing. It is alleged [by I. Kourbanis] that coalescing should improve soon, so that while we now get about 60% efficiencies from Accumulator to low beta, we should get about 80% after the coalescing upgrade. This roughly corresponds to 95% coalescing efficiency. Figure 15 shows the straight-scheme plot of the best Target Stack Size in this regime. The Target Stack Size remains the same for optimal performance, but the expected weekly luminosity increases by over 50%.

Other calculations could include the operation of the Collider in the Main Injector Era. This *should* be the topic of a future TM.

9. Conclusions.

A good model for Collider Operations exists. It accurately models the operational features of the Tevatron, the PBar Source and of shot setup. Some conclusions can be made on what criteria are to be used to determine when to end a store in the context of a real, up-and-down machine. In particular, strong conclusions can be made about the unacceptability of several possible criteria. The best and the most stable criterion to use is to end stores when the difference between the expected luminosity and the instantaneous luminosity is 9E30 cm^{-2} sec^{-1}. Target Stack Size Scheme or the Ratio Scheme are also acceptable. Parameters describing a typical store and a typical week can be calculated. Some predictions on the nature of the Collider after improvements can be made. Work on this model continues.

A nice benefit of this model has been in developing intuition on the operation of the Collider. In particular, I and the other Run Coordinators now have a much better idea about what to expect in day-to-day operations.

FIGURE 1

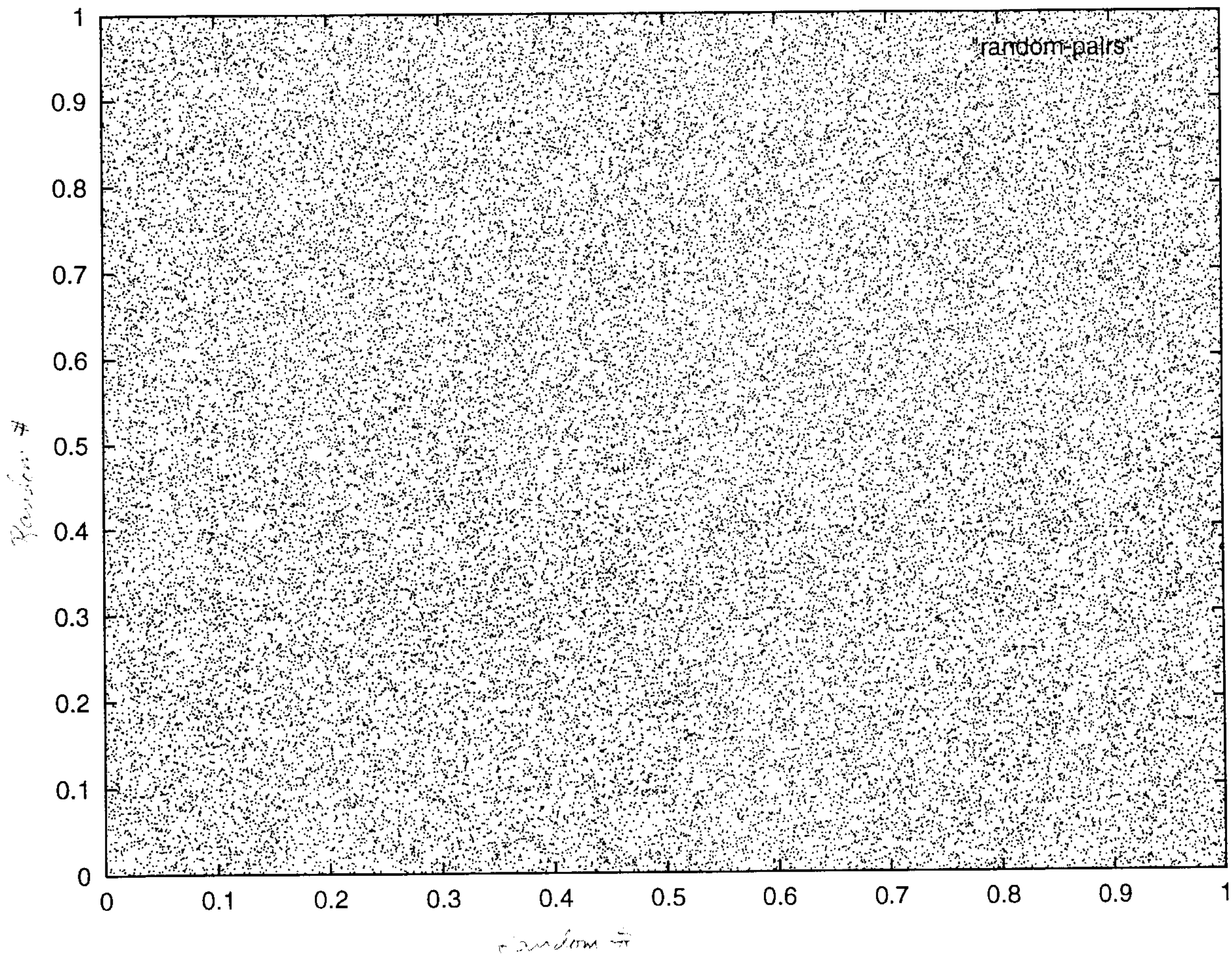


Figure 2

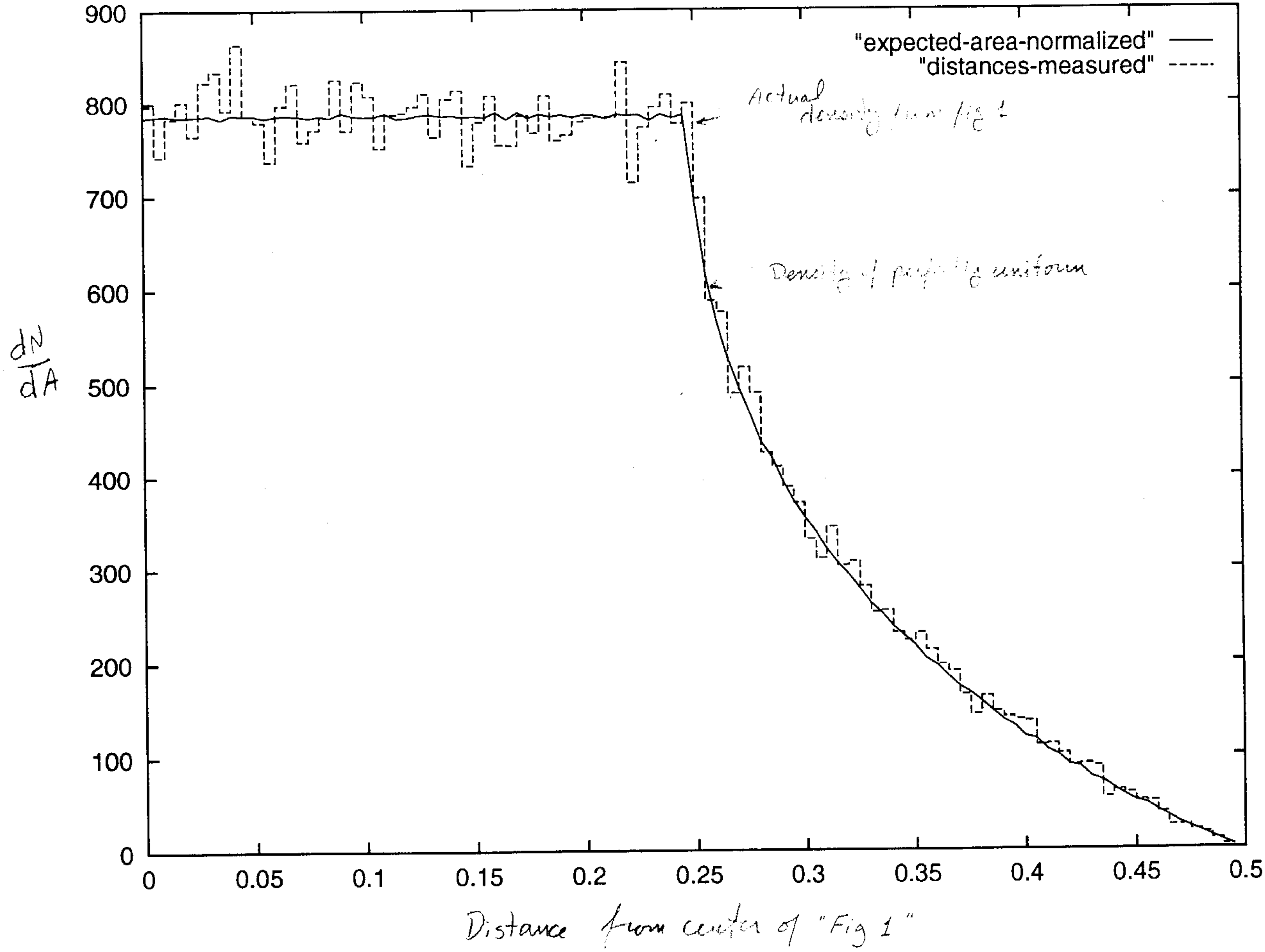
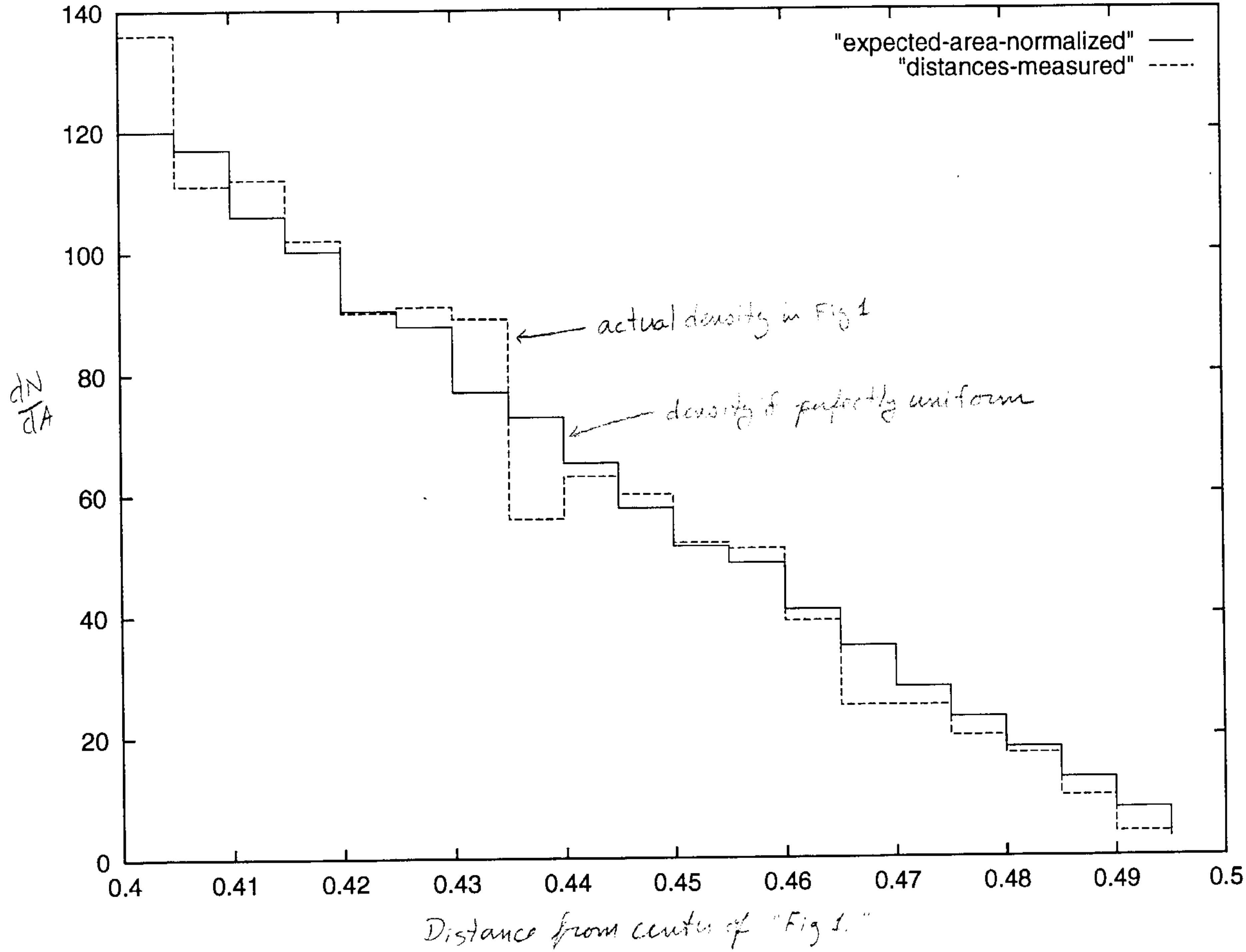

"expected-area-normalized"
"distances-measured"
900
800
700
600
500
400
300
200
100
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
dN/dA
Distance from center of "Fig 1"

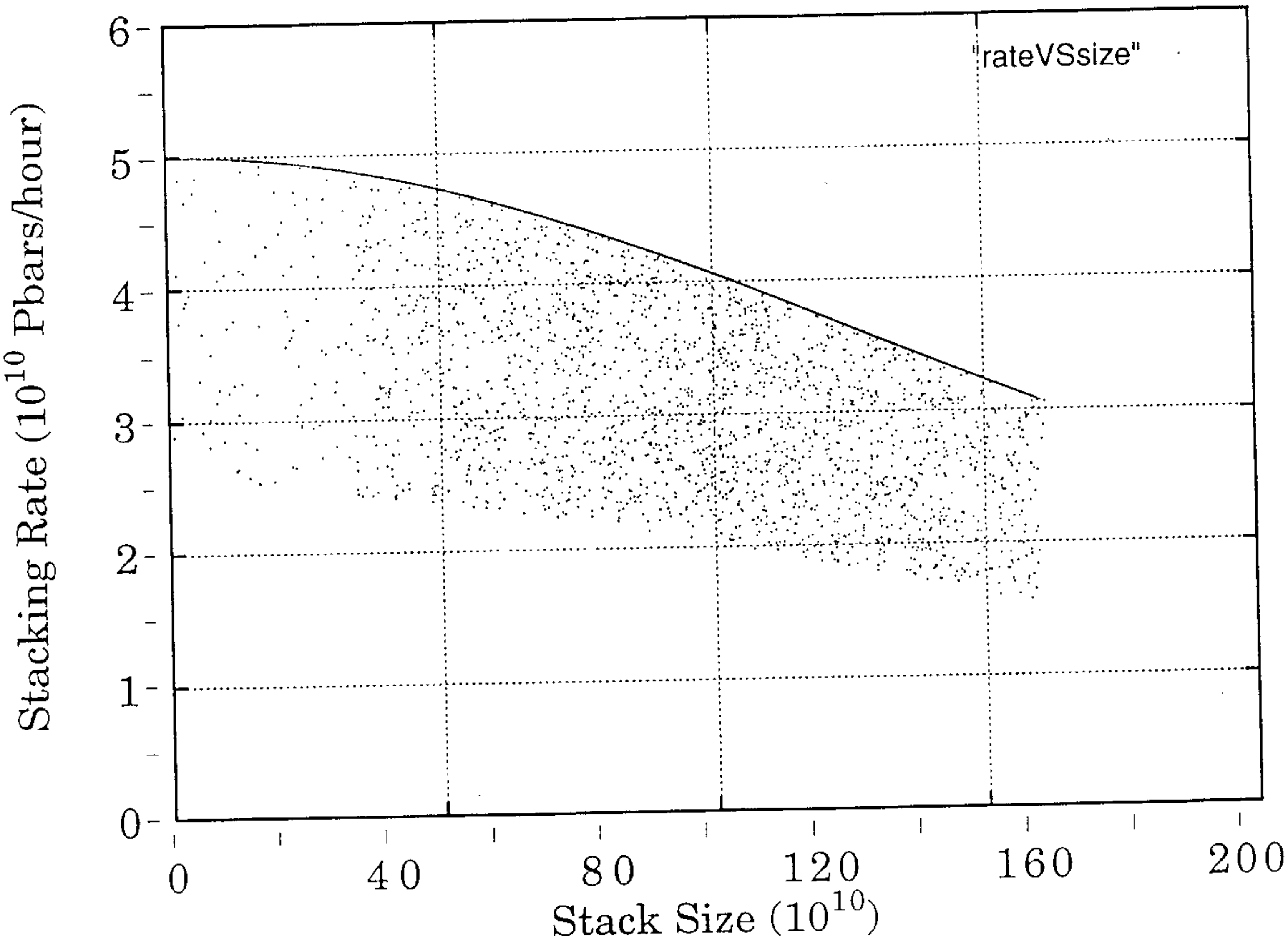
Figure 3


"expected-area-normalized"
"distances-measured"
actual density in Fig 1
density of perfectly uniform
140
120
100
80
60
40
20
0
0.4
0.41
0.42
0.43
0.44
0.45
0.46
0.47
0.48
0.49
0.5
$\frac{dN}{dA}$
Distance from center of "Fig 1."

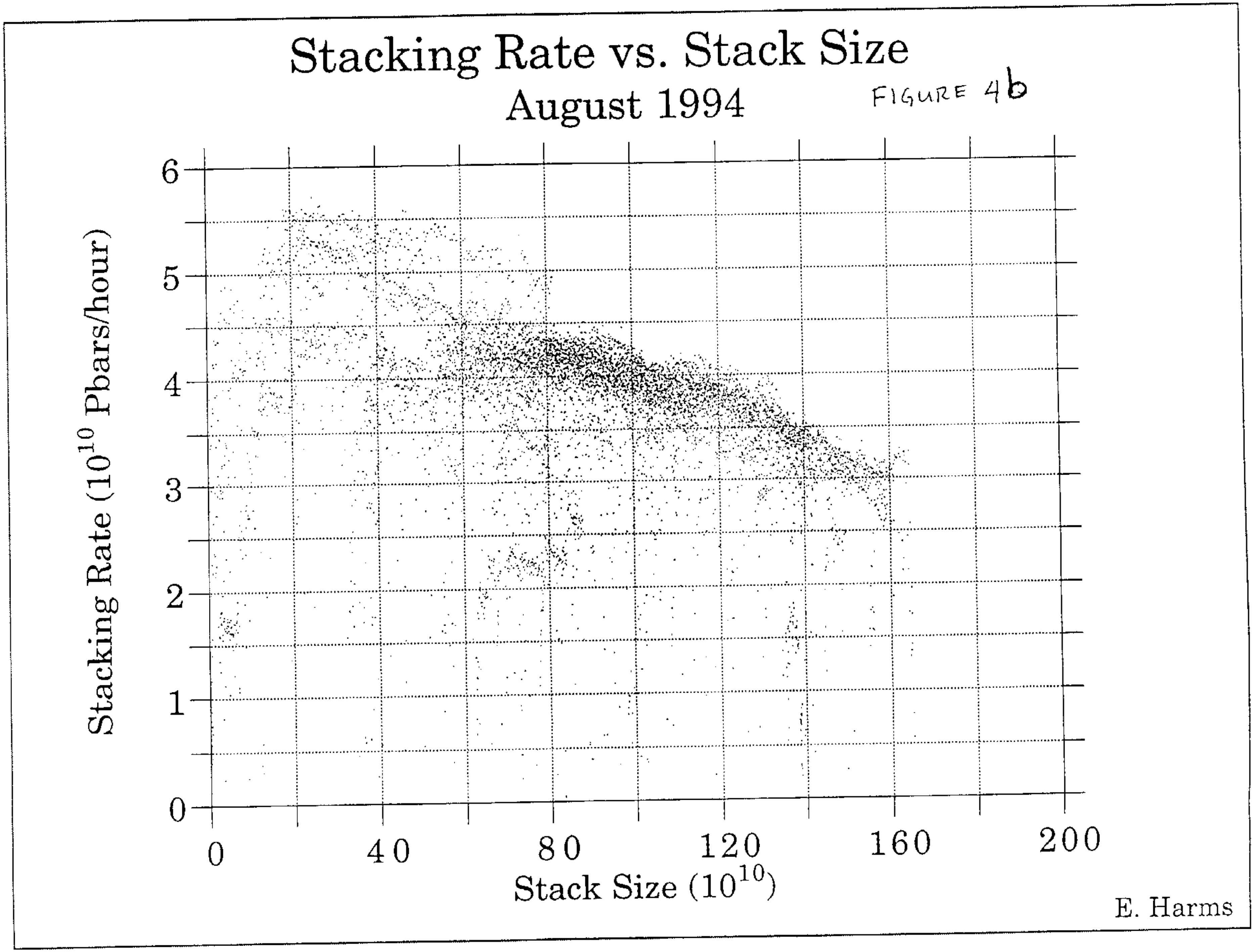
Stacking Rate vs. Stack Size

~~August 1994~~ SIMULATION

Figure 4a

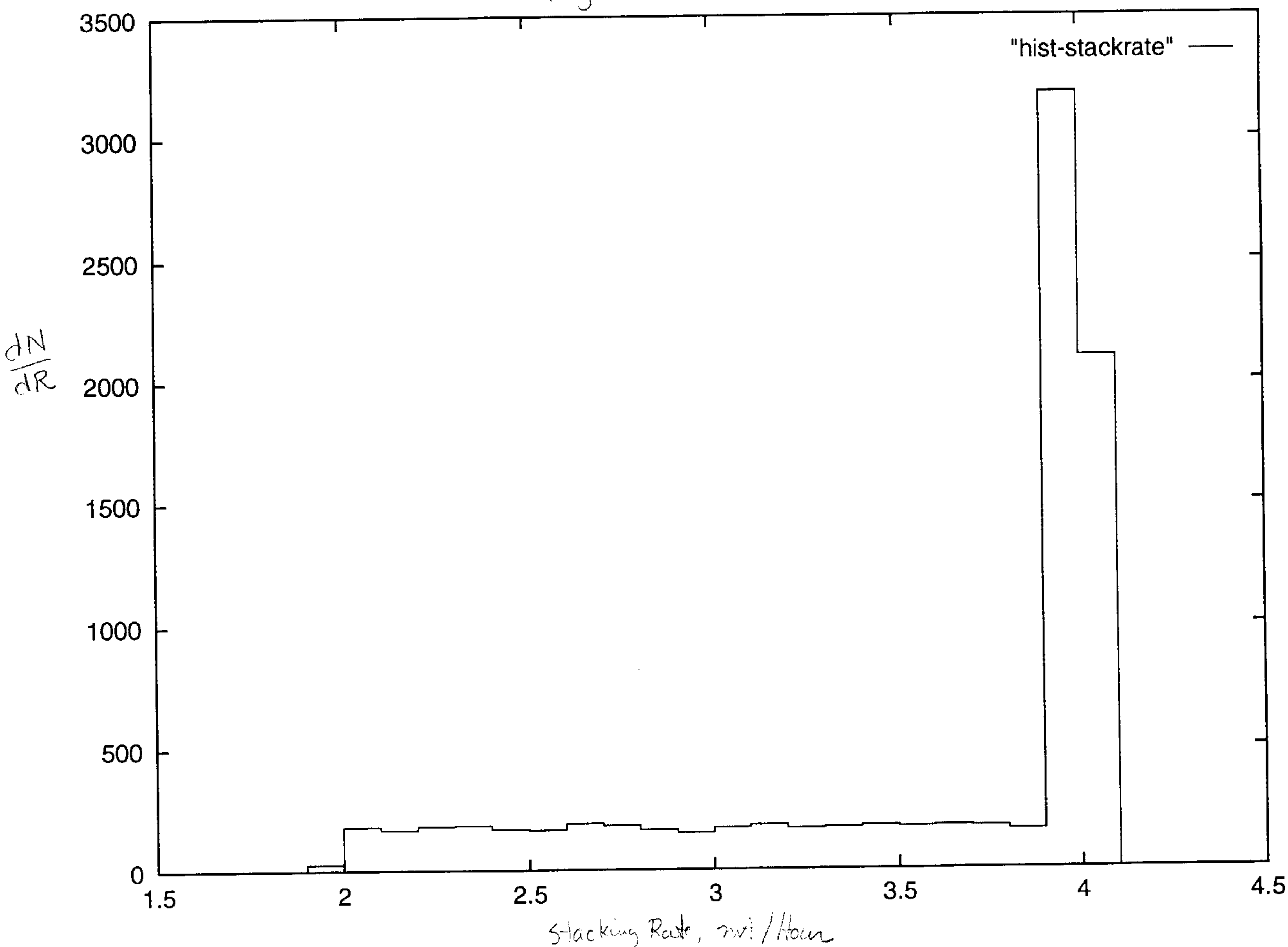


E. ~~Harms~~ McCrory

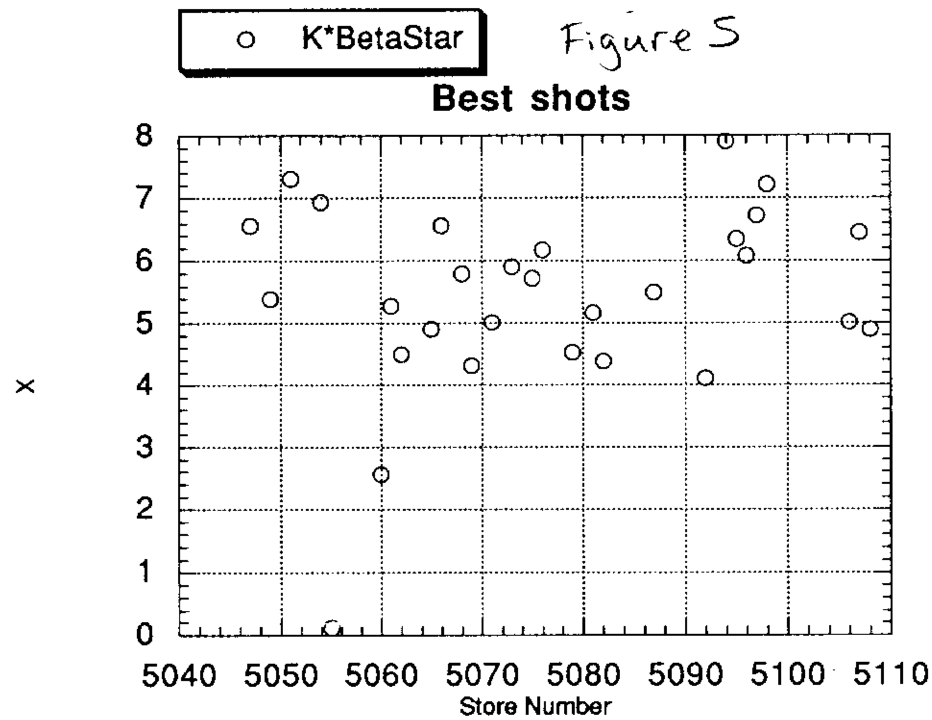


Stacking Rate vs. Stack Size
August 1994
FIGURE 4b
6
5
4
3
2
1
0
Stacking Rate (10^10 Pbars/hour)
0
40
80
120
160
200
Stack Size (10^10)
E. Harms

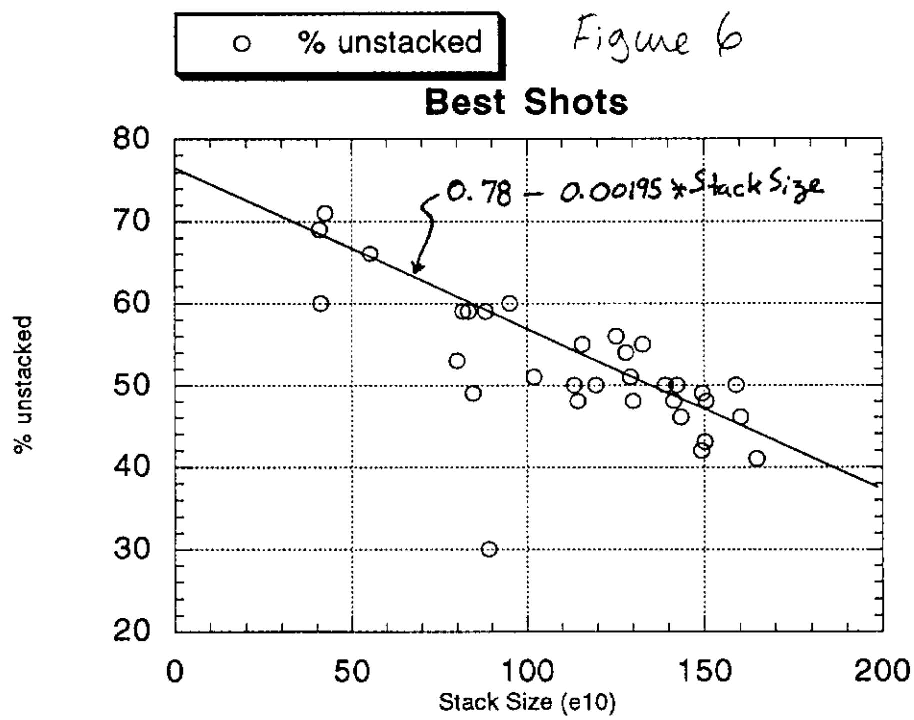
Figure 4c



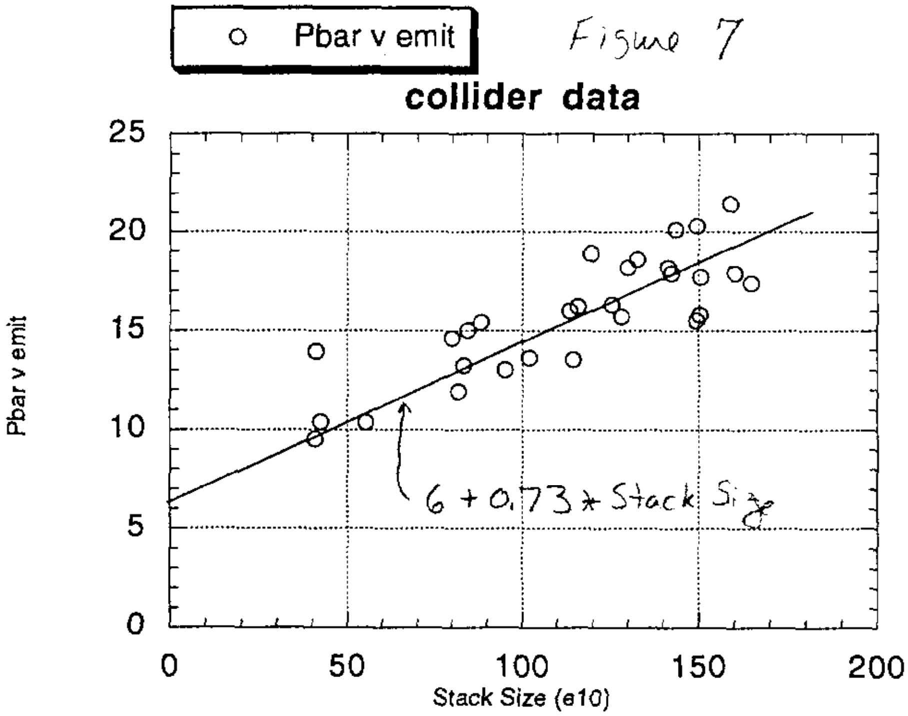
"hist-stackrate"
3500
3000
2500
2000
1500
1000
500
0
1.5
2
2.5
3
3.5
4
4.5
dN/dR
Stacking Rate, mA/Hour



K*BetaStar
Figure 5
Best shots
X
Store Number
8
7
6
5
4
3
2
1
0
5040
5050
5060
5070
5080
5090
5100
5110



% unstacked
Figure 6
Best Shots
% unstacked
Stack Size (e10)
0.78 – 0.00195 * Stack Size
80
70
60
50
40
30
20
0
50
100
150
200


Pbar v emit
Figure 7
collider data
25
20
15
10
5
0
0
50
100
150
200
Pbar v emit
Stack Size (e10)
6 + 0.73 * Stack Size

Stack< 100· effic = 0.6

Stack>100· Effic = 0.6 − (0.00167 * (StackSize − 100))

Figure 8a

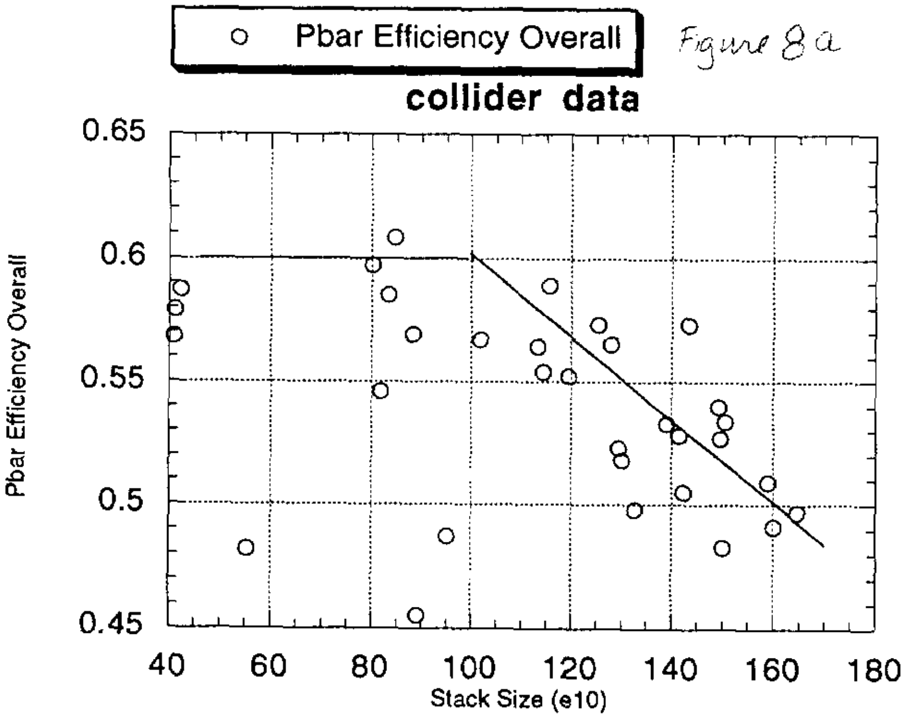
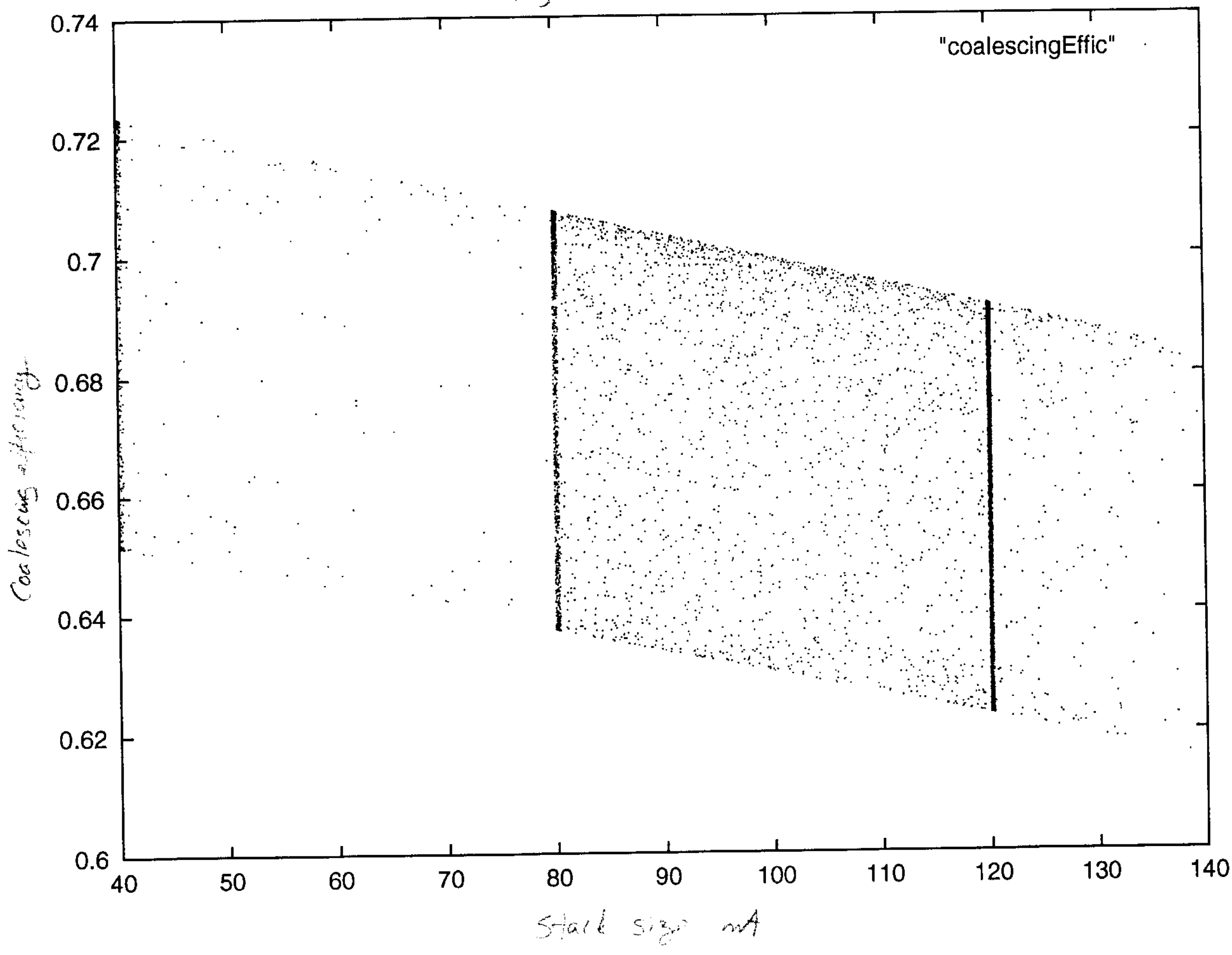
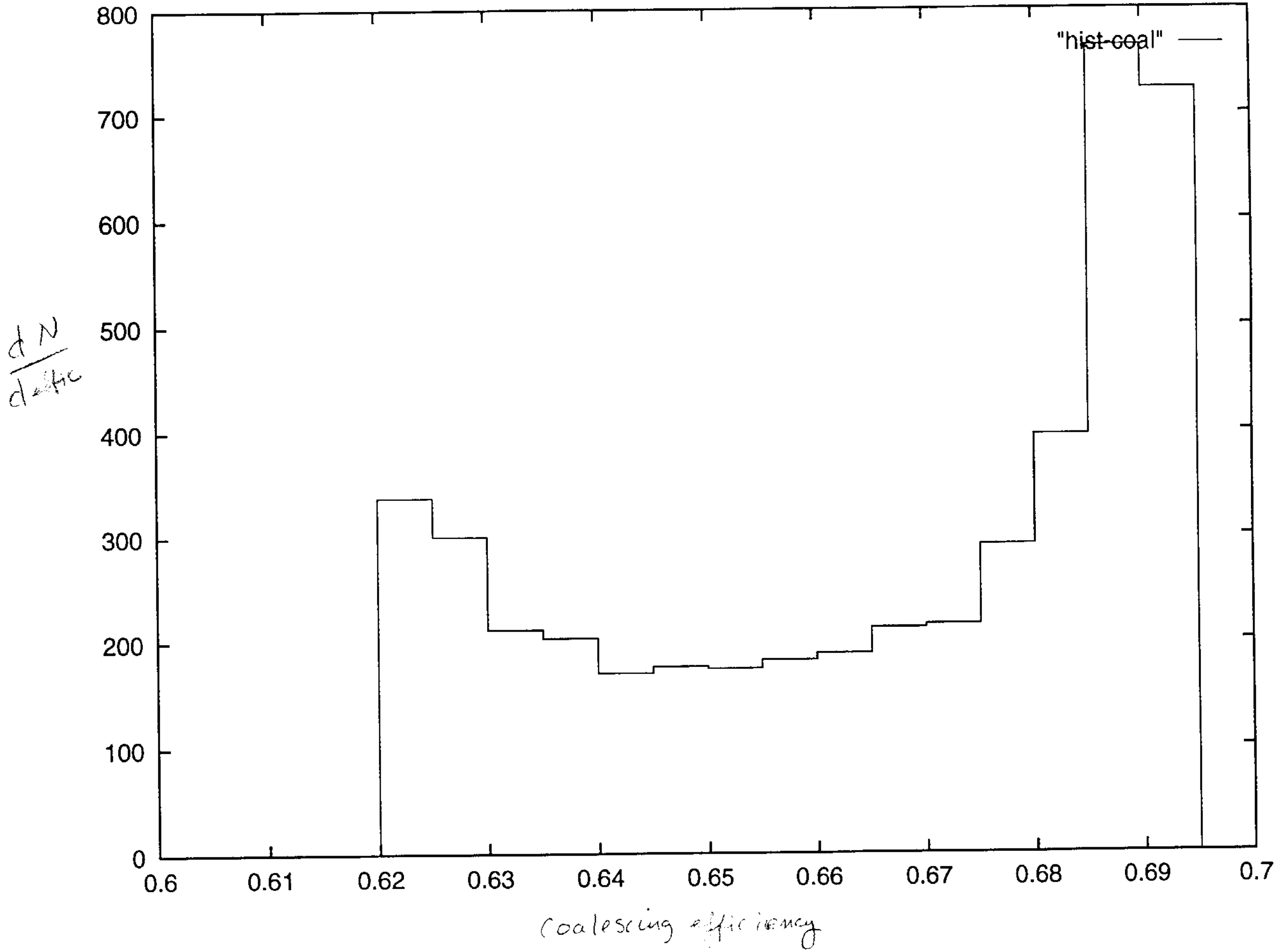


Figure 8b



"coalescingEffic"
0.74
0.72
0.7
0.68
0.66
0.64
0.62
0.6
40
50
60
70
80
90
100
110
120
130
140
Coalescing efficiency
Stack size mA

Figure 8C



"hist-coal"
800
700
600
500
400
300
200
100
0
0.6
0.61
0.62
0.63
0.64
0.65
0.66
0.67
0.68
0.69
0.7
dN/d effic
coalescing efficiency

FIGURE 9

Comparison of Model Results with Real Data

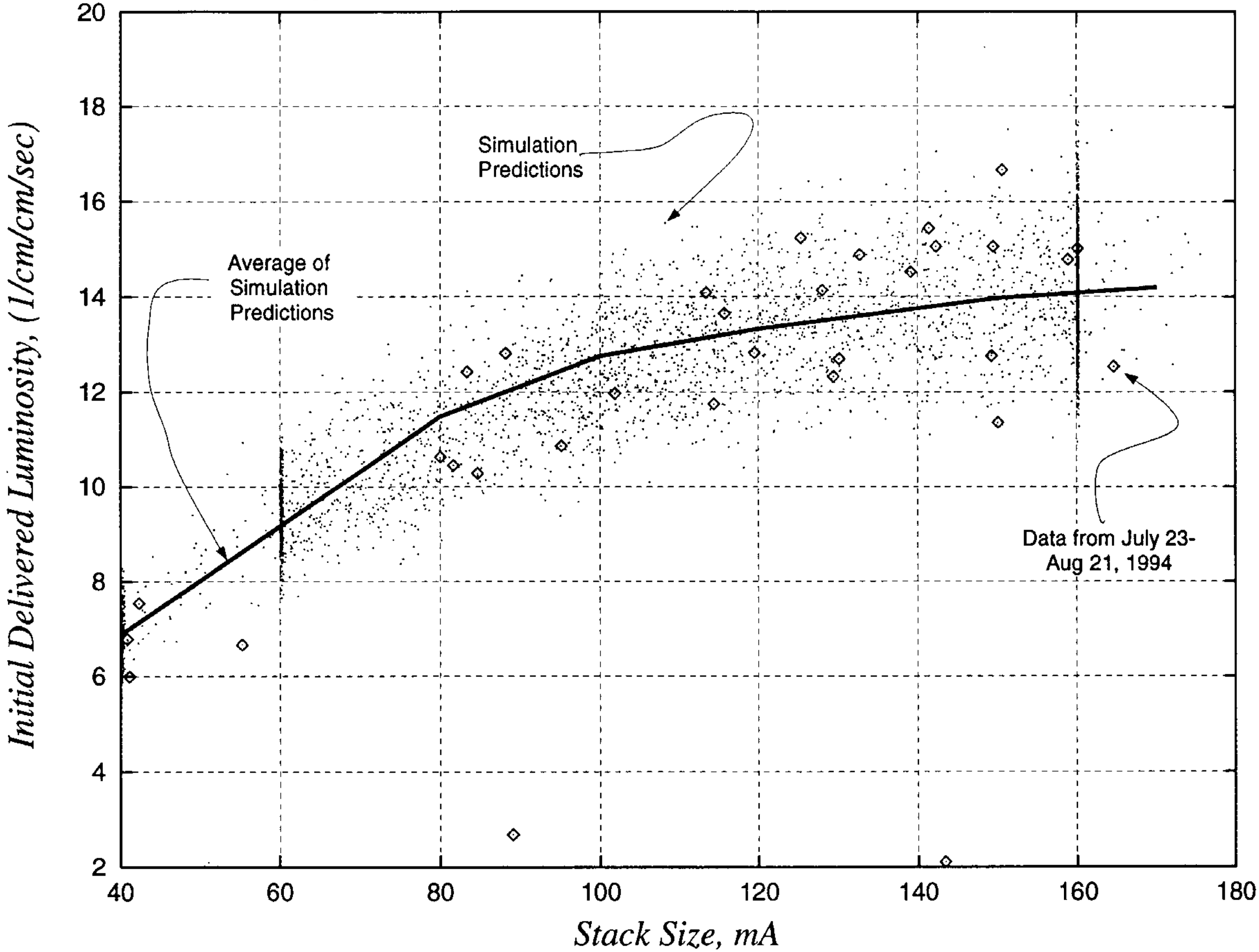


Figure 10a

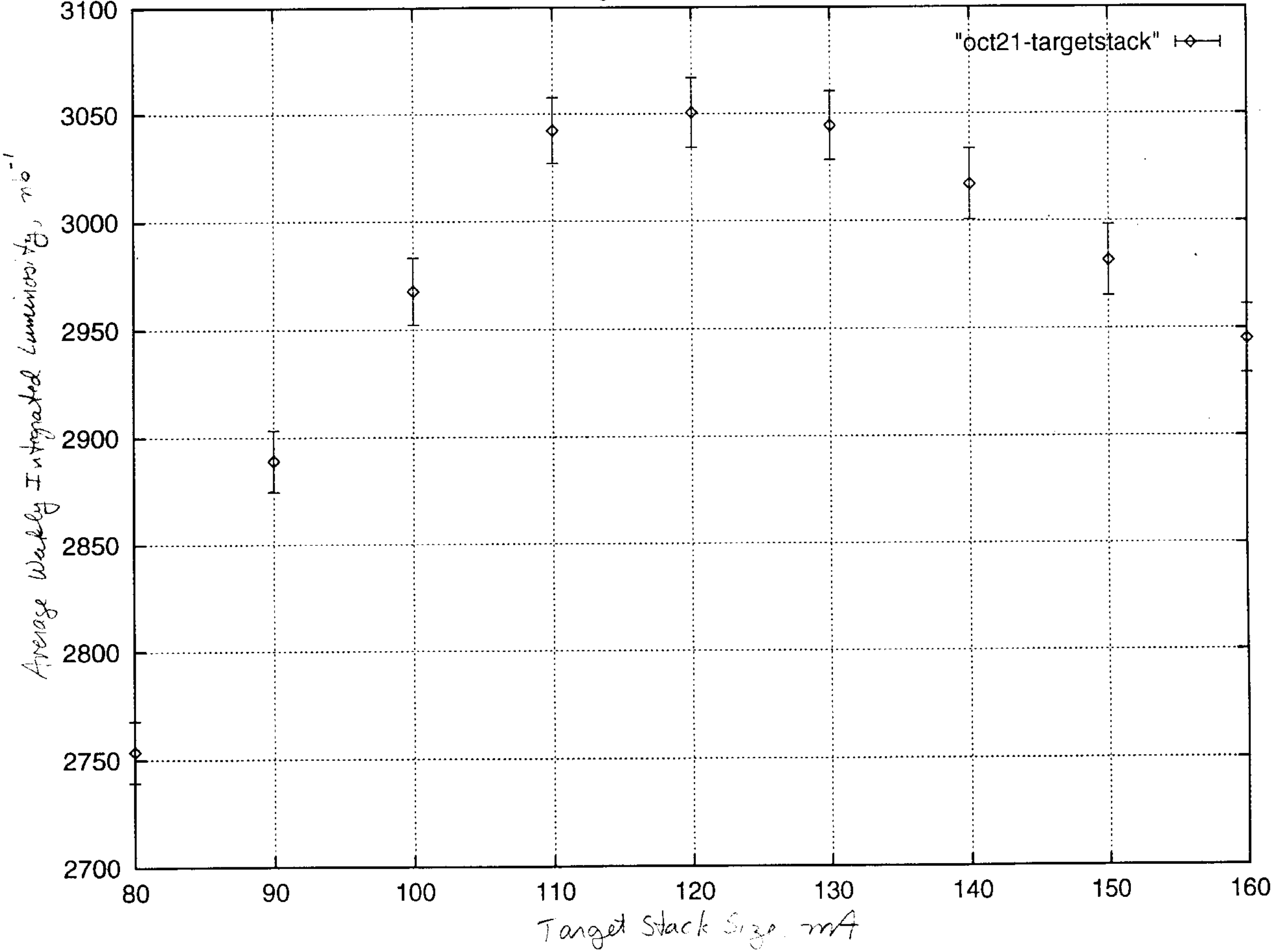
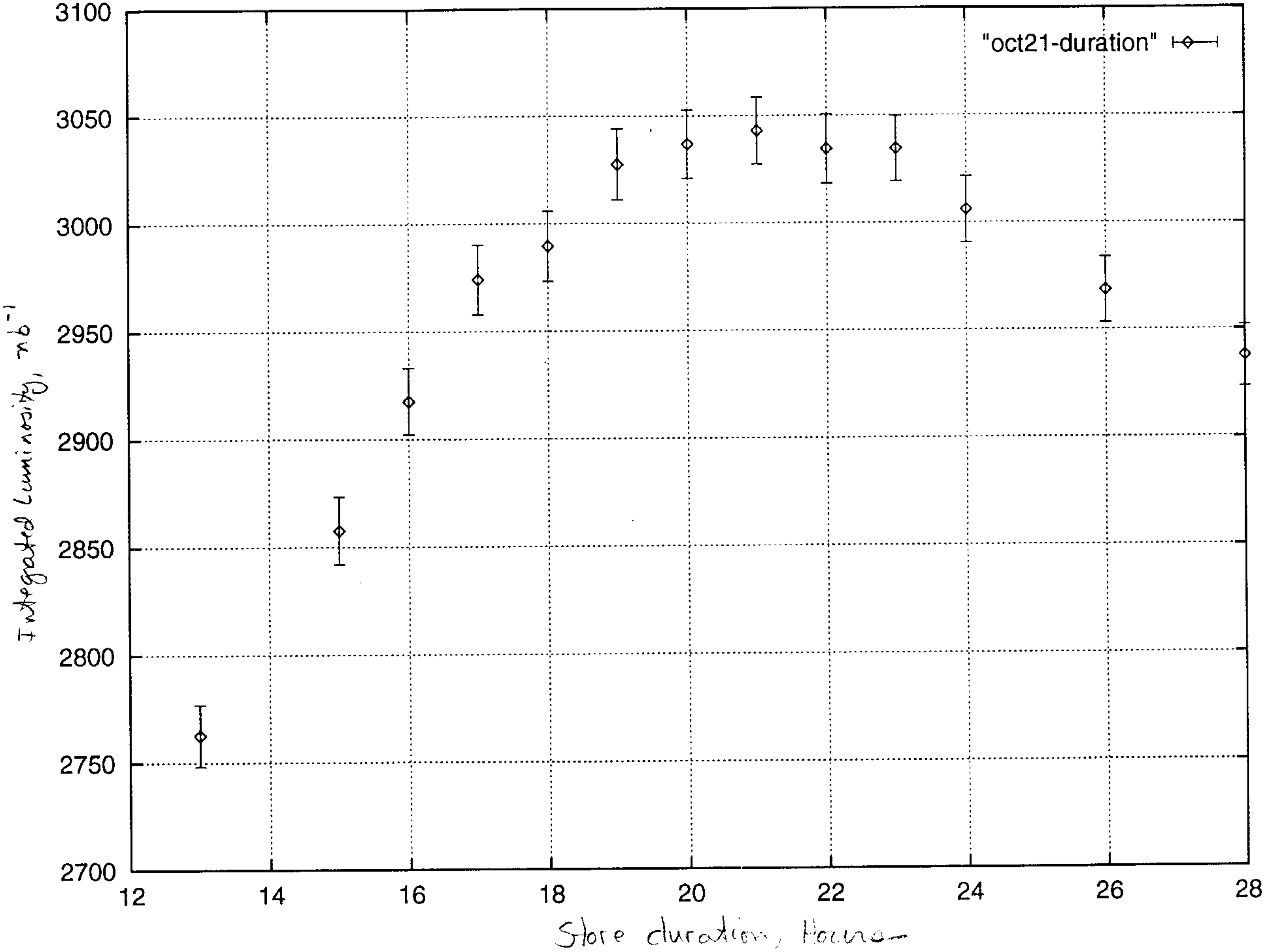
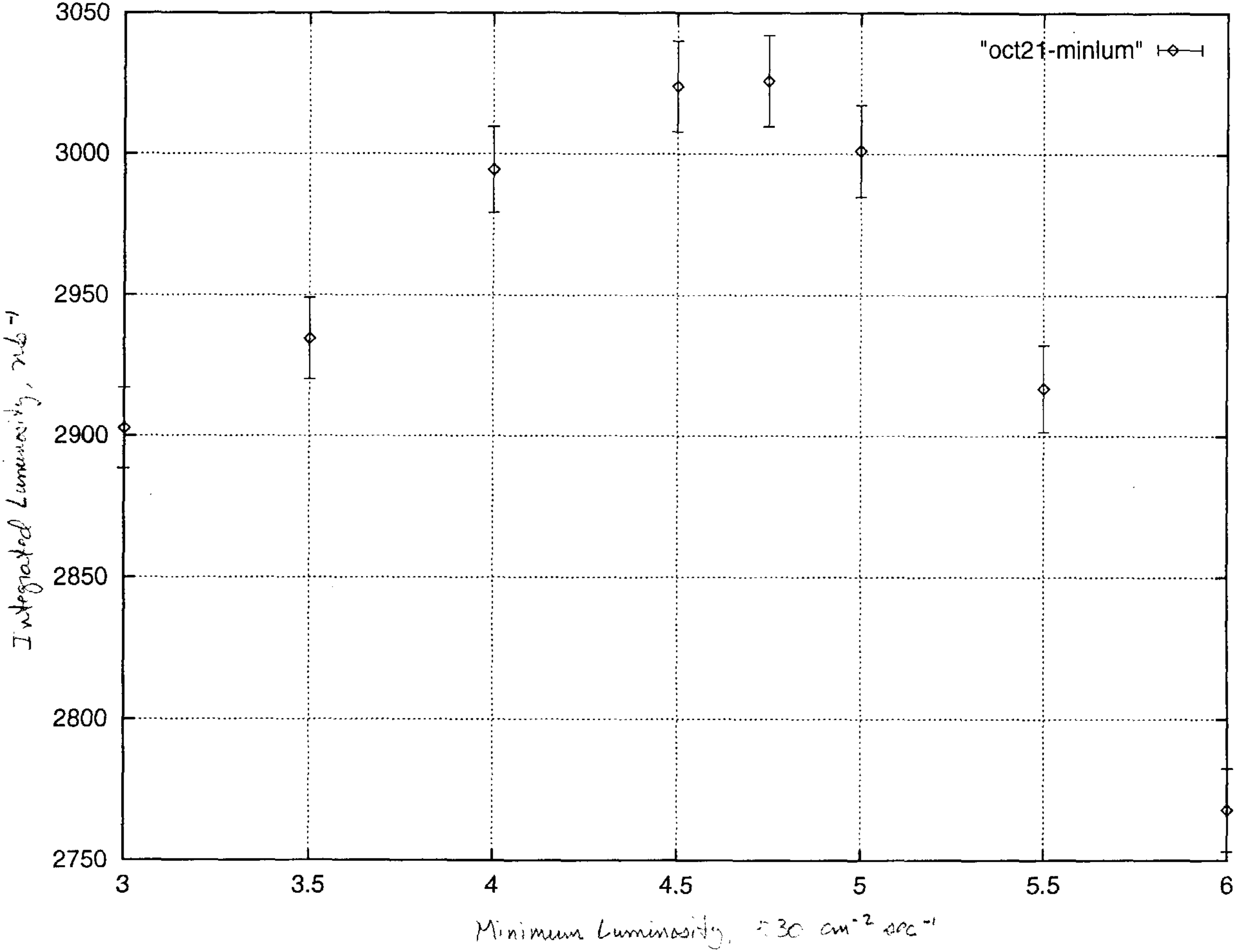

"oct21-targetstack"
3100
3050
3000
2950
2900
2850
2800
2750
2700
80
90
100
110
120
130
140
150
160
Average Weekly Integrated Luminosity, nb⁻¹
Target Stack Size, mA

Figure 10b



"oct21-duration"
3100
3050
3000
2950
2900
2850
2800
2750
2700
12
14
16
18
20
22
24
26
28
Integrated Luminosity, nb^{-1}
Store duration, Hours

Figure 10 C



"oct21-minlum"
3050
3000
2950
2900
2850
2800
2750
3
3.5
4
4.5
5
5.5
6
Integrated Luminosity, nb⁻¹
Minimum Luminosity, E30 cm⁻² sec⁻¹

Figure 10d

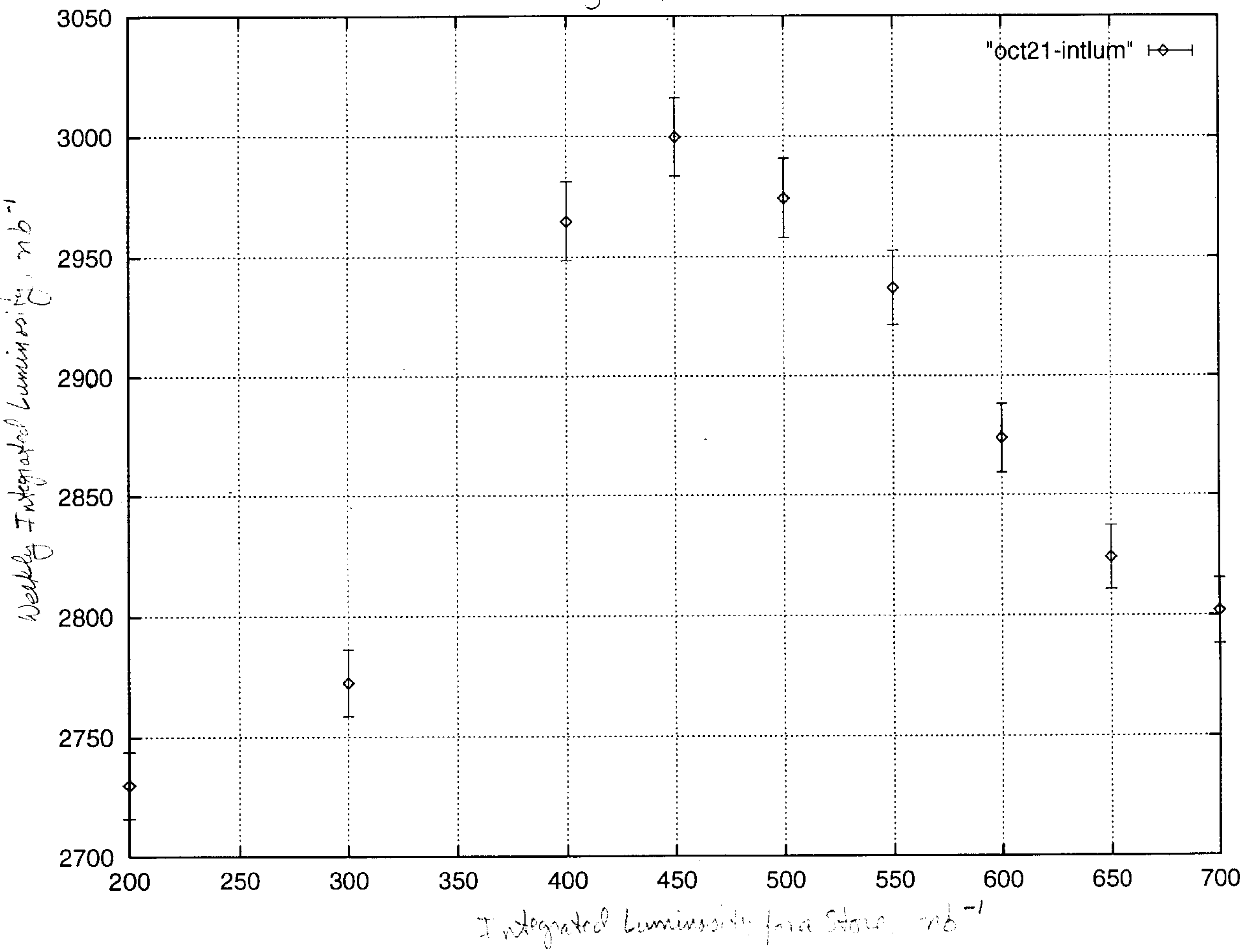
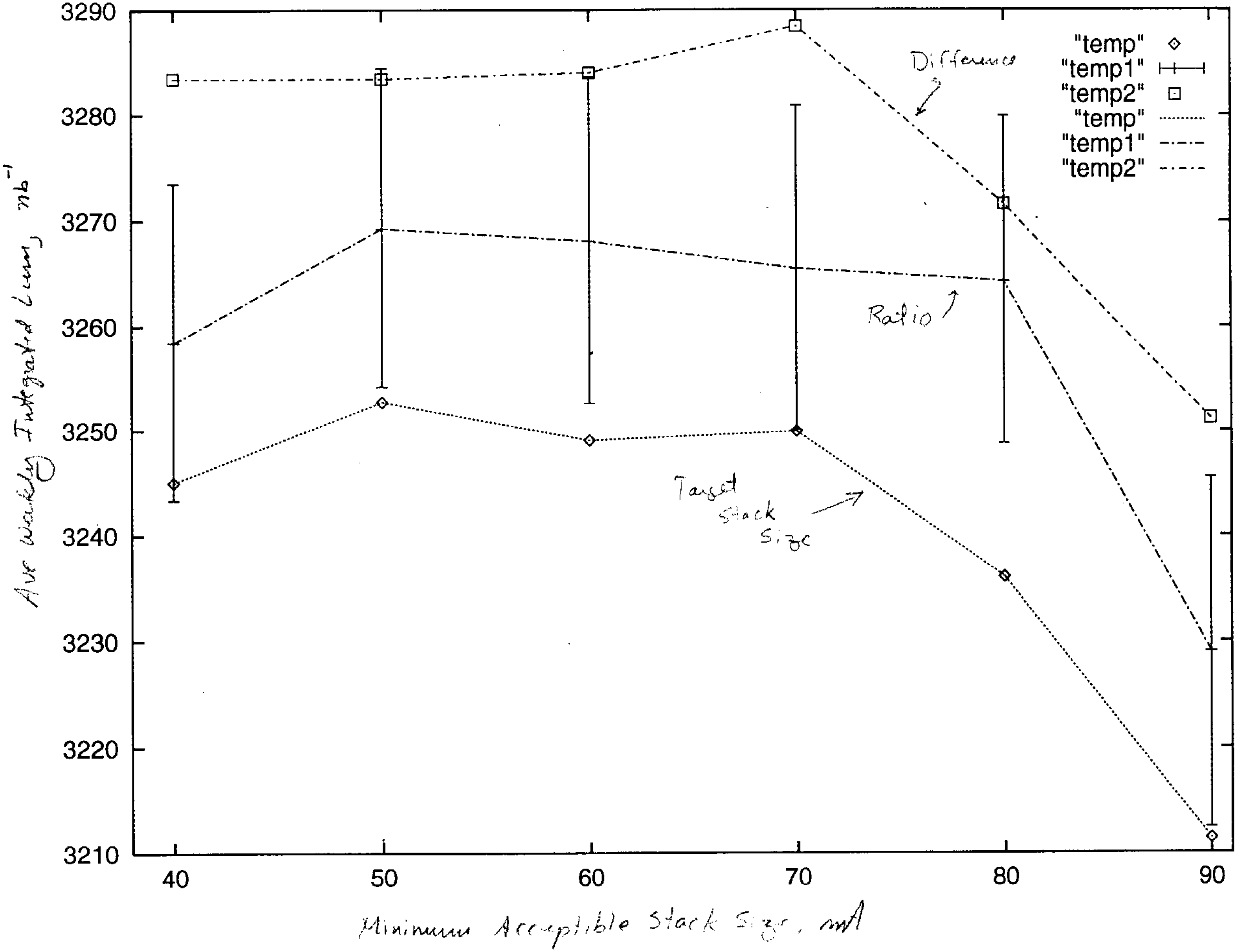
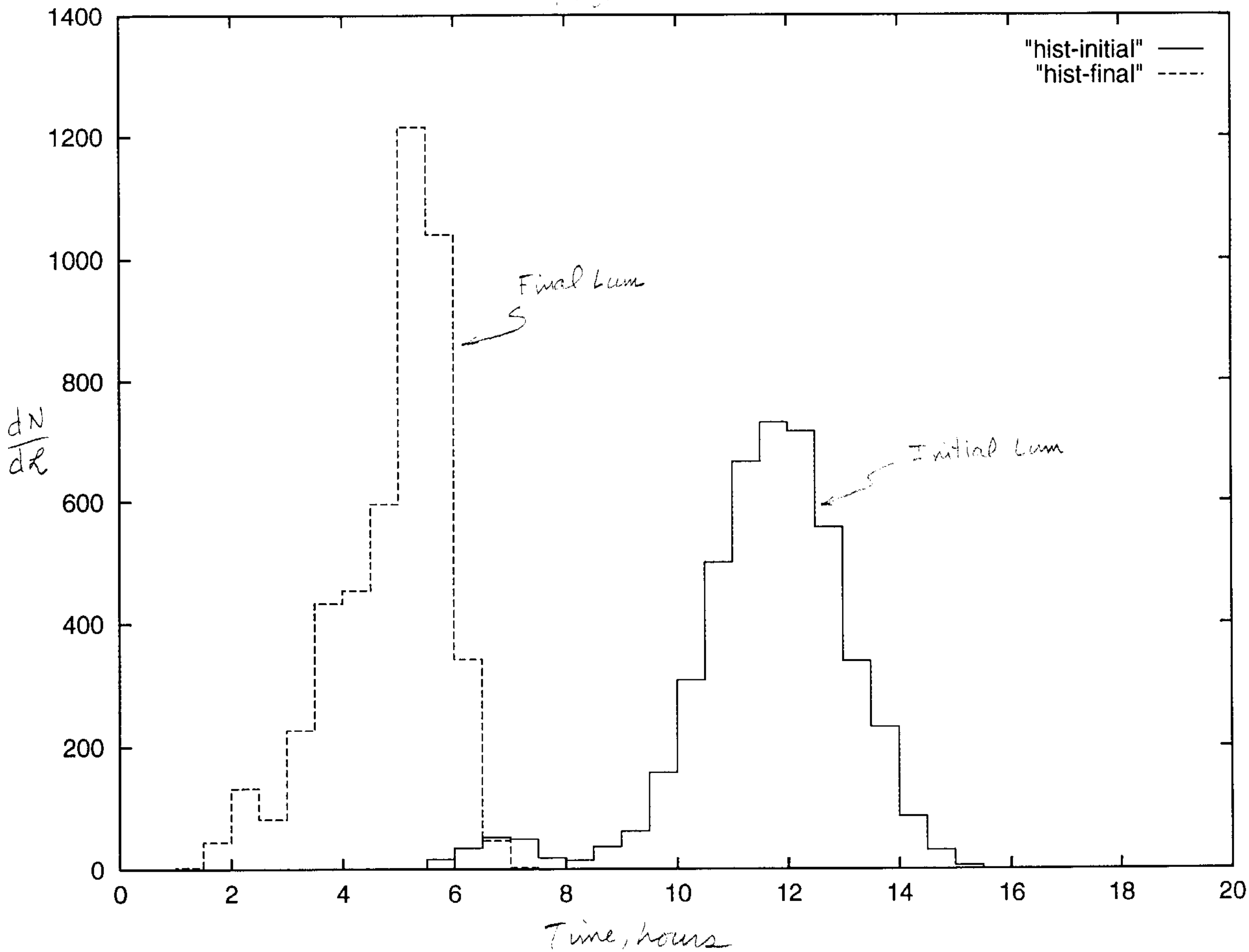

"oct21-intlum"
3050
3000
2950
2900
2850
2800
2750
2700
200
250
300
350
400
450
500
550
600
650
700
Weekly Integrated Luminosity, nb-1
Integrated Luminosity for a Store, nb-1

FIGURE 11



3290
3280
3270
3260
3250
3240
3230
3220
3210
40
50
60
70
80
90
"temp"
"temp1"
"temp2"
"temp"
"temp1"
"temp2"
Difference
Ratio
Target Stack Size
Ave Weekly Integrated Lum, nb⁻¹
Minimum Acceptible Stack Size, mA

Figure 12a



"hist-initial"
"hist-final"
Final Lum
Initial Lum
1400
1200
1000
800
600
400
200
0
0
2
4
6
8
10
12
14
16
18
20
dN/dL
Time, hours

Figure 12b

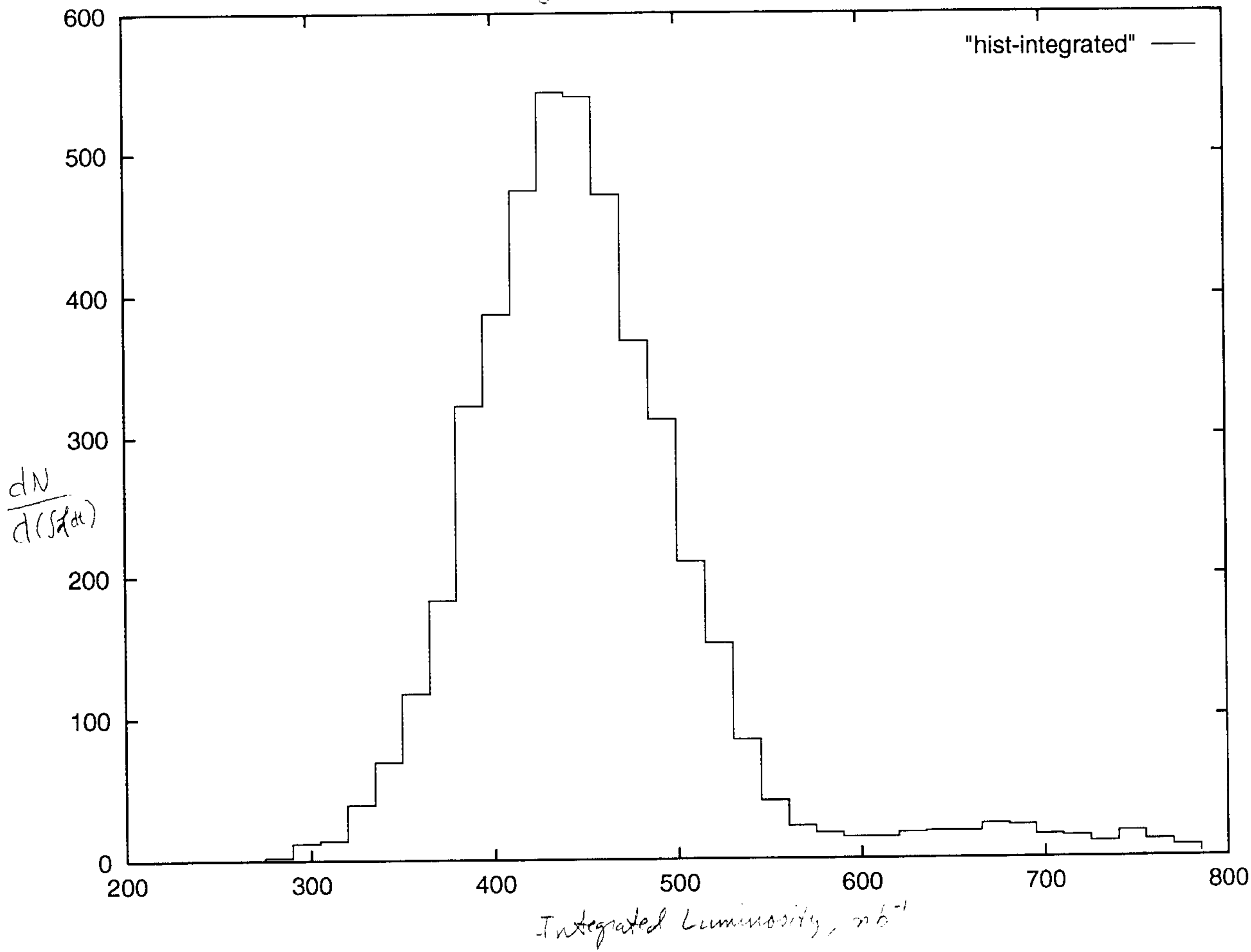
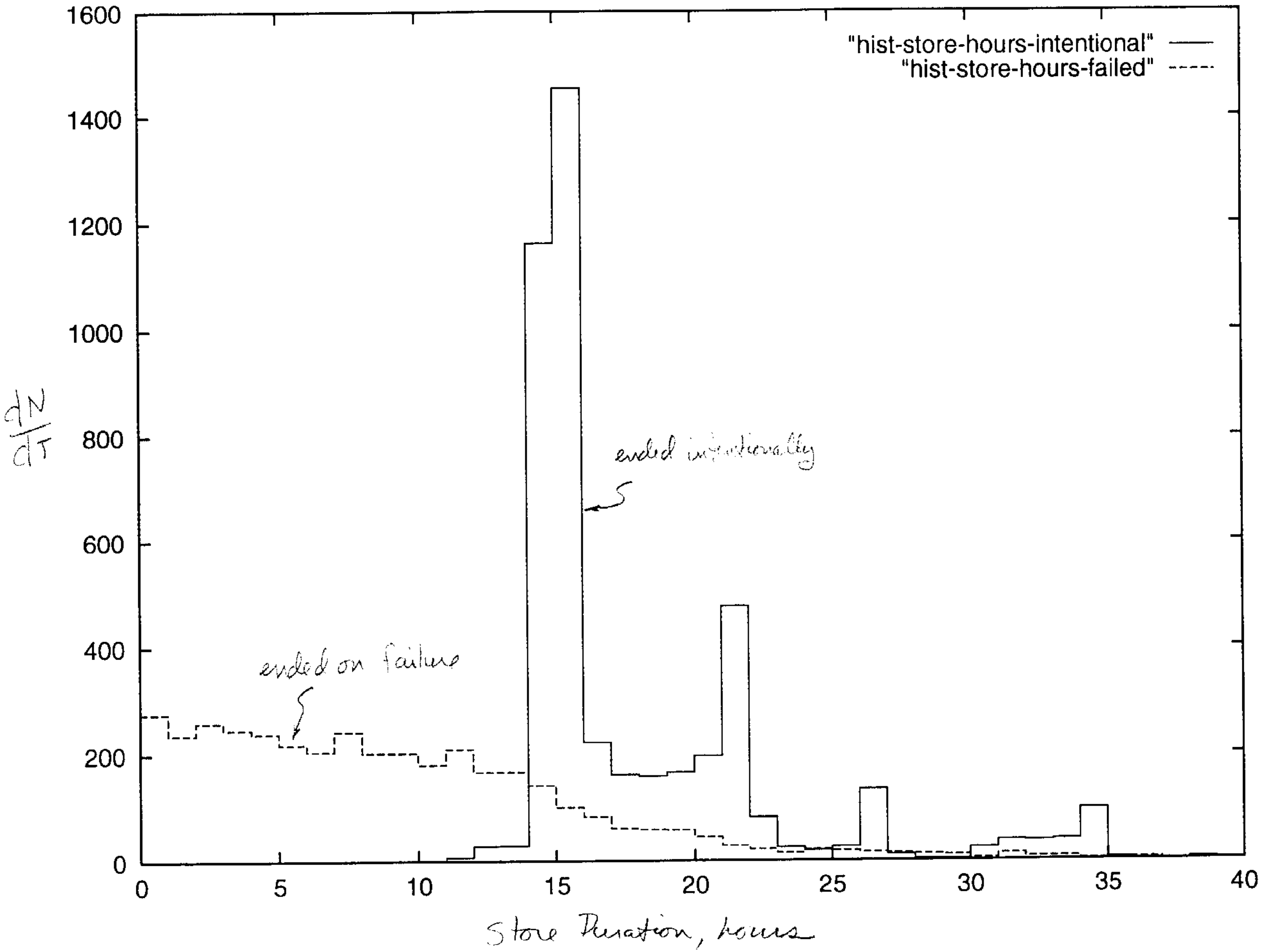
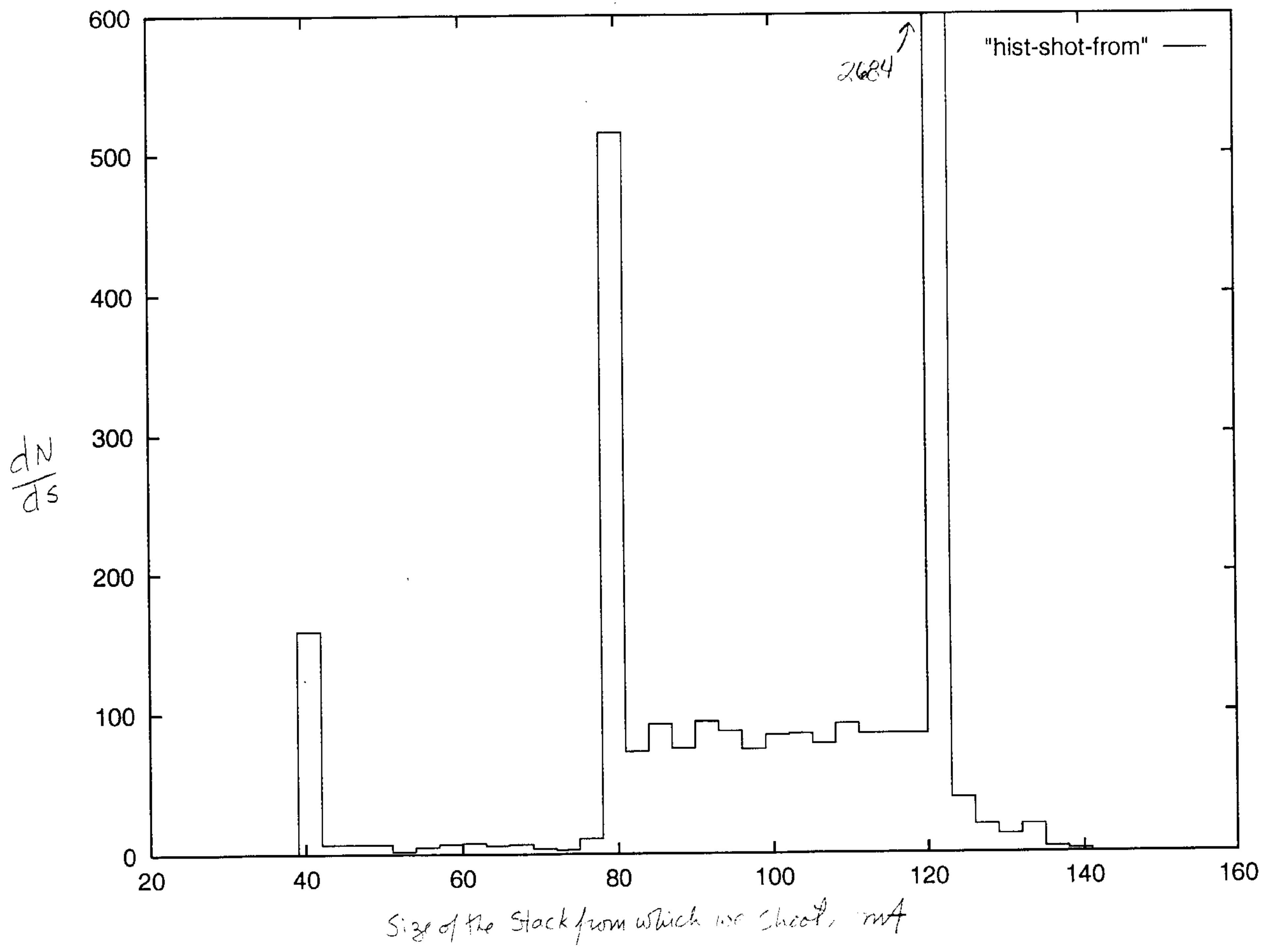

"hist-integrated"
600
500
400
300
200
100
0
200
300
400
500
600
700
800
dN / d(∫ℒdt)
Integrated Luminosity, nb⁻¹

Figure 12C



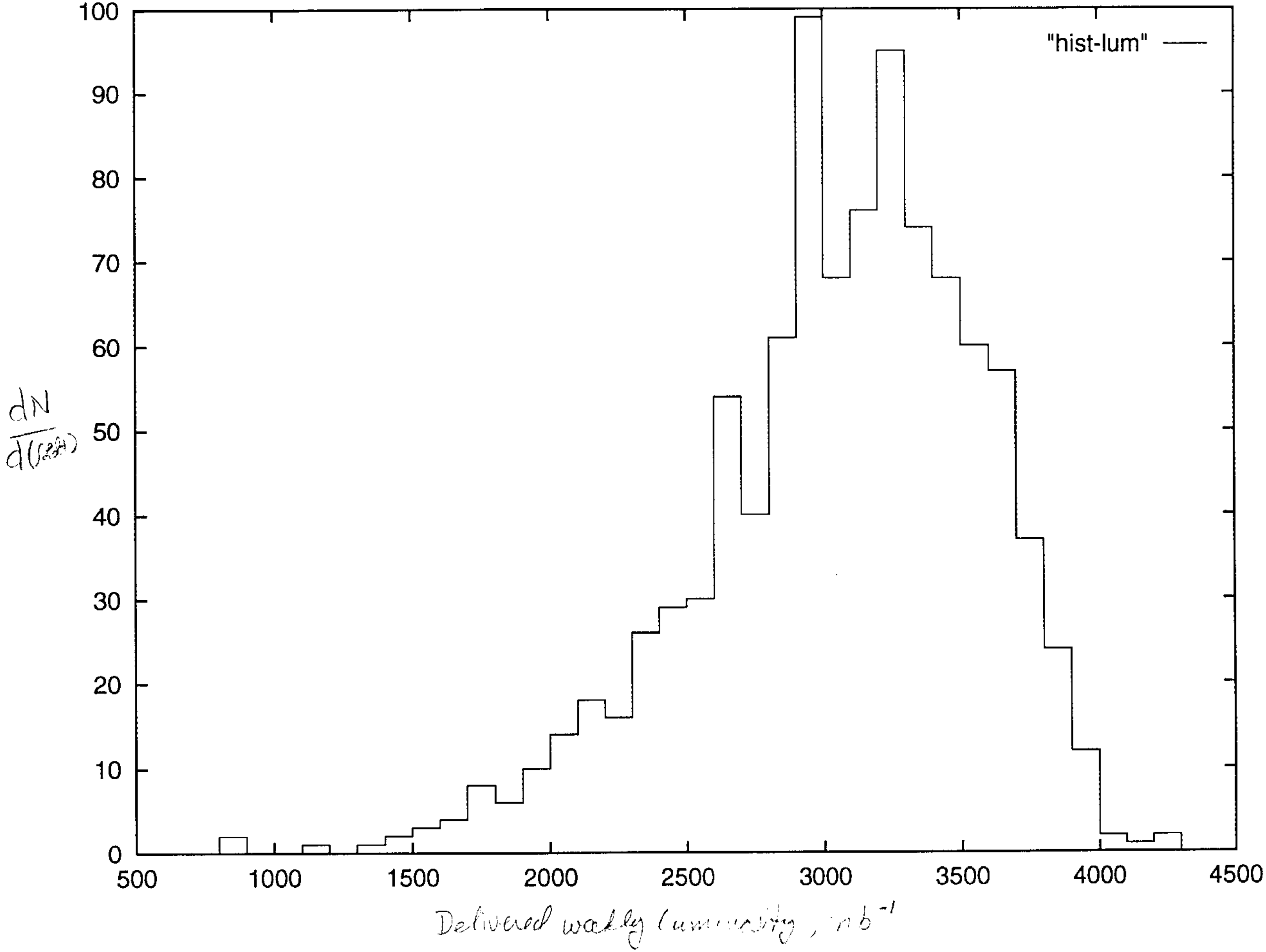
"hist-store-hours-intentional"
"hist-store-hours-failed"
1600
1400
1200
1000
800
600
400
200
0
0
5
10
15
20
25
30
35
40
dN/dT
ended intentionally
ended on failure
Store Duration, hours

Figure 12d



"hist-shot-from"
2684
600
500
400
300
200
100
0
20
40
60
80
100
120
140
160
dN/ds
Size of the Stack from which we Shoot, mA

Figure 13a



100
90
80
70
60
50
40
30
20
10
0
500
1000
1500
2000
2500
3000
3500
4000
4500
"hist-lum"
dN
Delivered weekly luminosity, nb⁻¹

Figure 13b

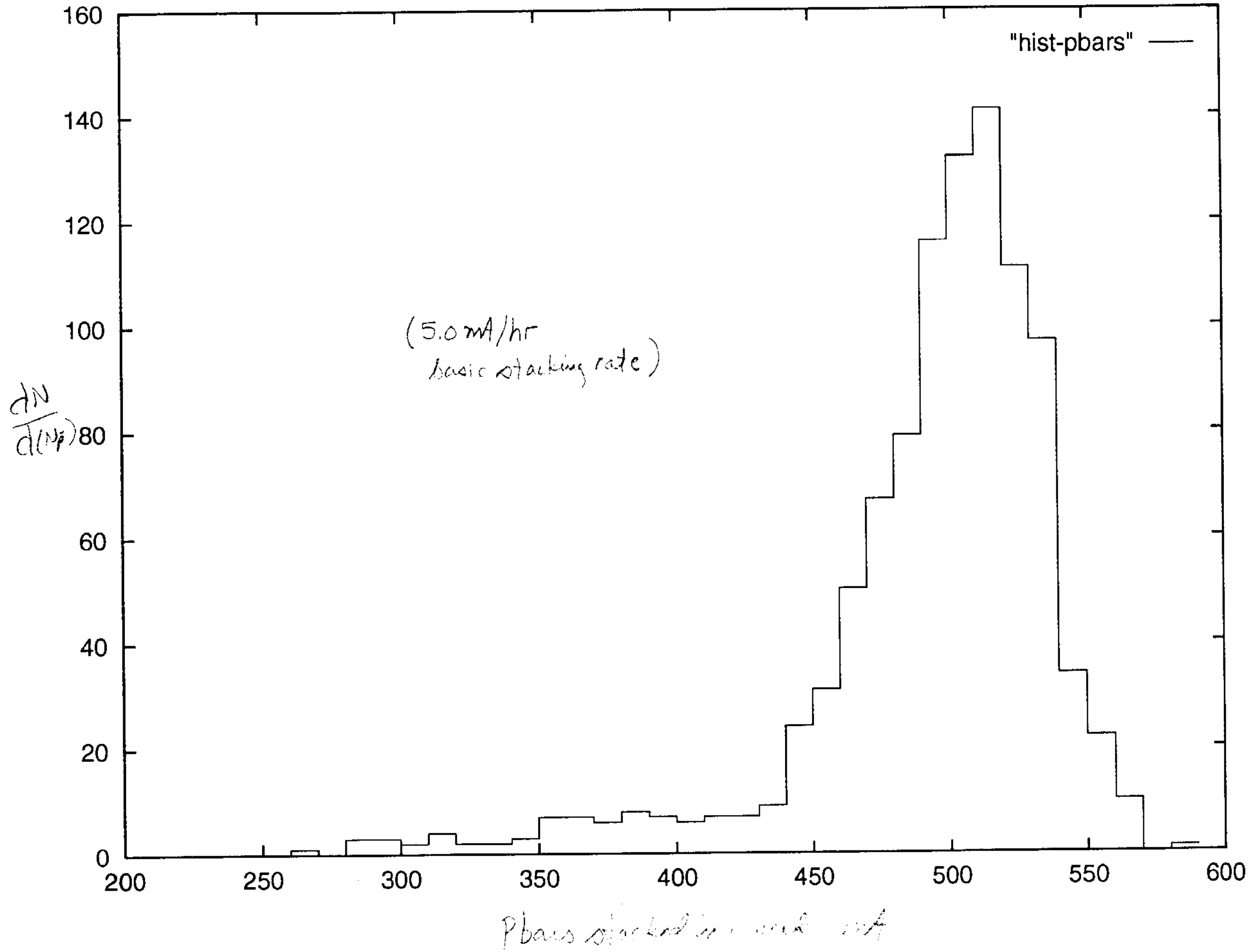
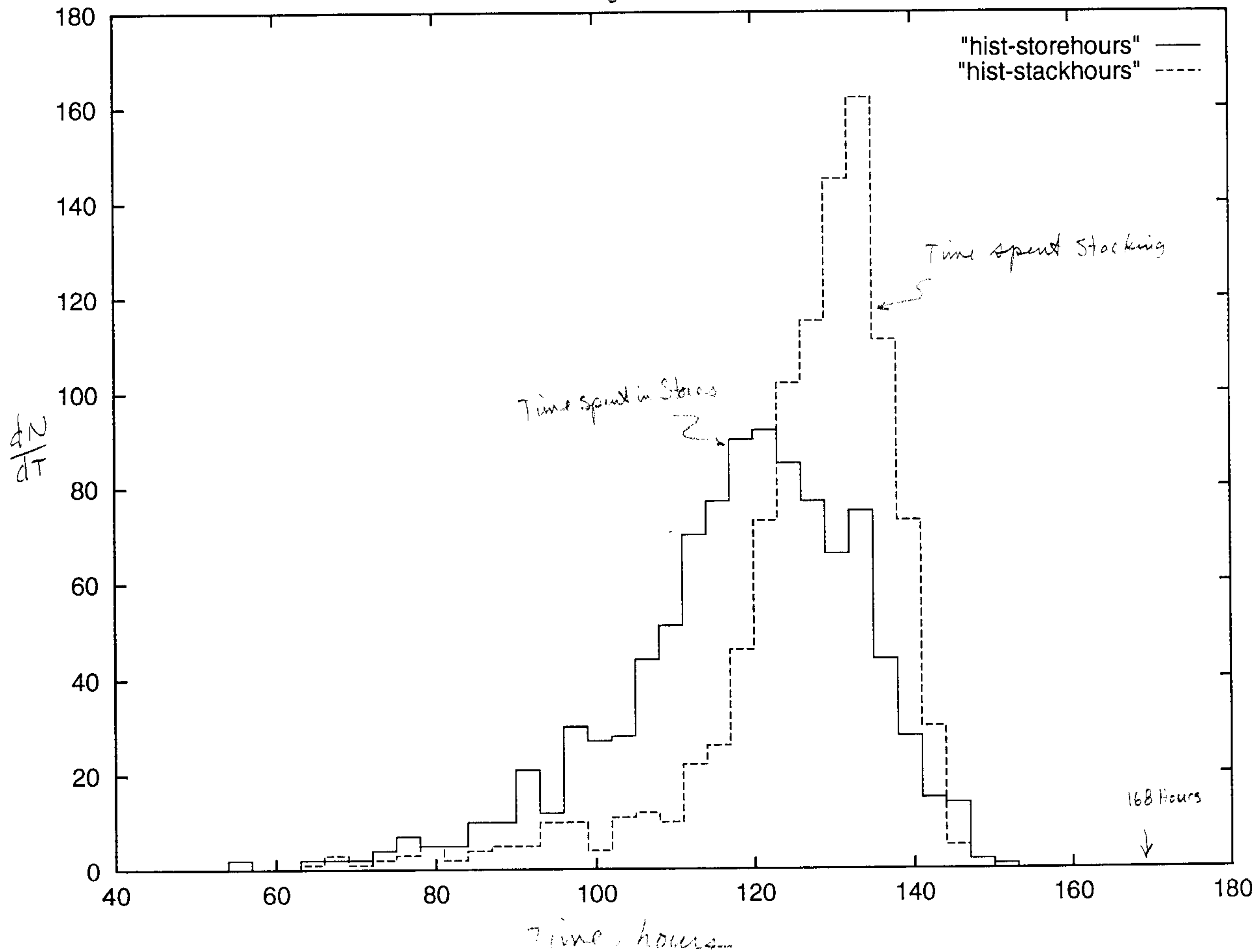

"hist-pbars"
(5.0 mA/hr
basic stacking rate)
dN/d(Np)
0
20
40
60
80
100
120
140
160
200
250
300
350
400
450
500
550
600

Figure 13C



"hist-storehours"
"hist-stackhours"
Time spent Stacking
Time spent in Stores
168 Hours
dN/dT
Time, hours
0
20
40
60
80
100
120
140
160
180
40
60
80
100
120
140
160
180

Figure 13d

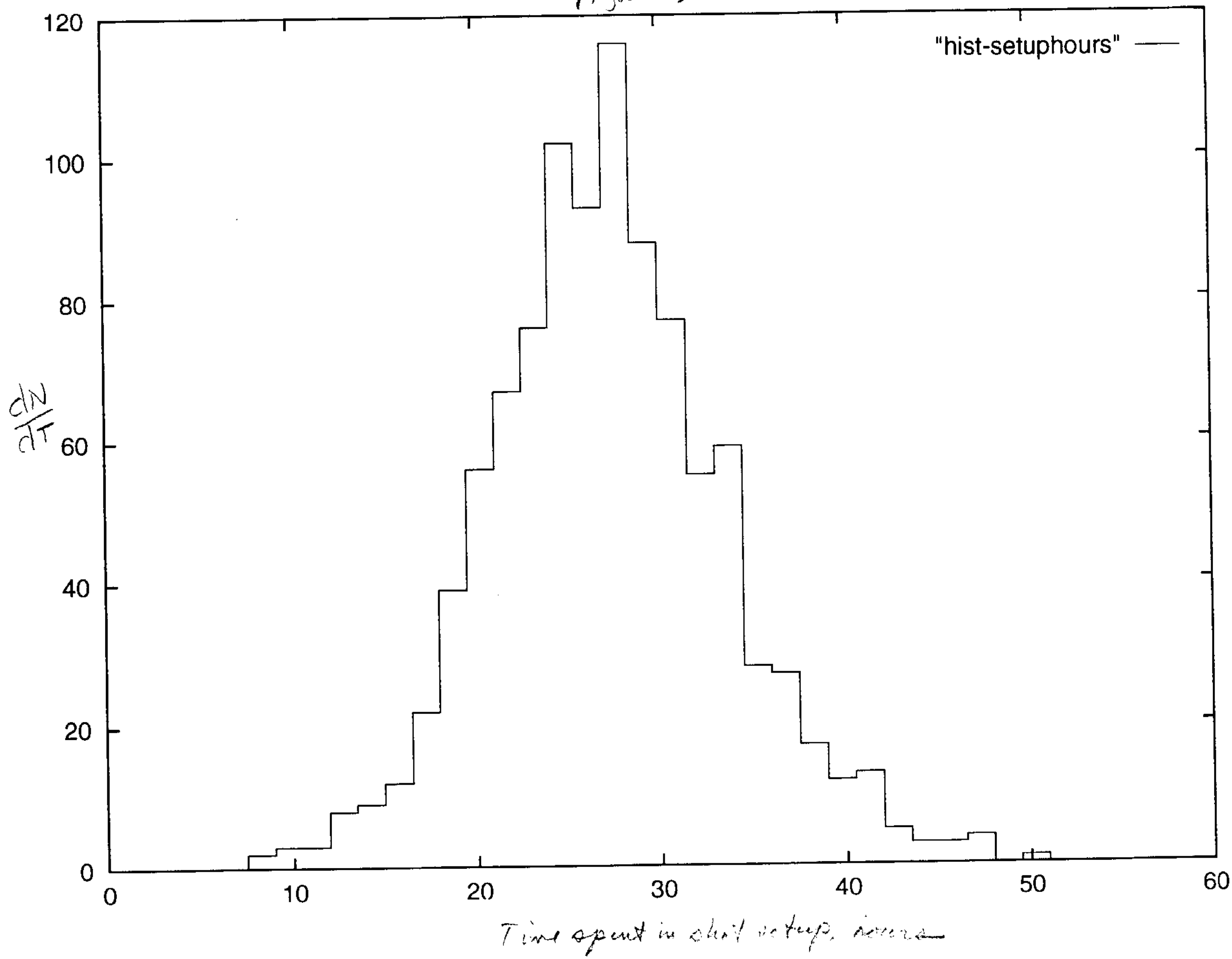
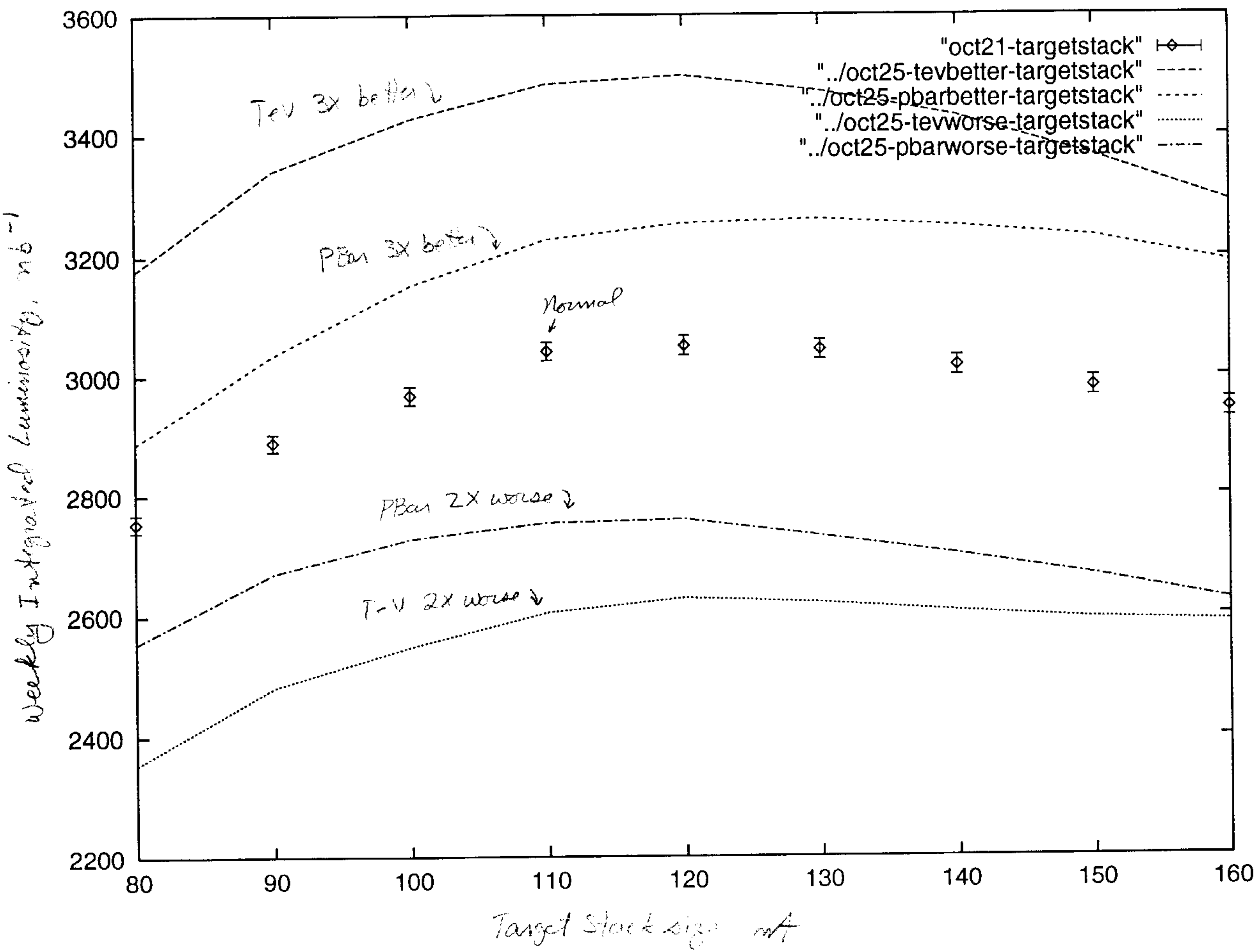
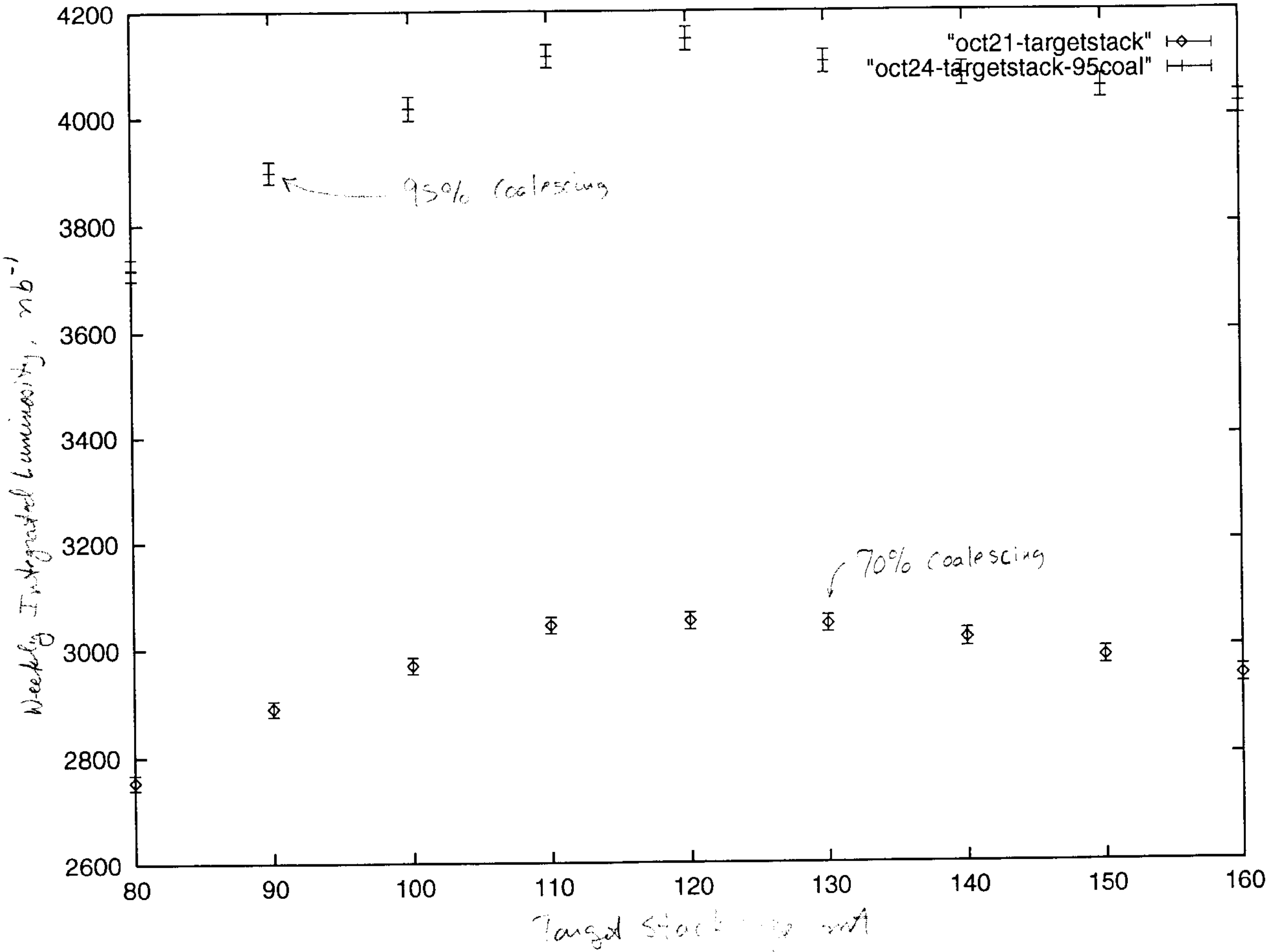

"hist-setuphours"
dN/dT
0
20
40
60
80
100
120
0
10
20
30
40
50
60
Time spent in shift setup, hours

Figure 14



"oct21-targetstack"
"../oct25-tevbetter-targetstack"
"../oct25-pbarbetter-targetstack"
"../oct25-tevworse-targetstack"
"../oct25-pbarworse-targetstack"
TeV 3x better
PBar 3X better
Normal
PBar 2X worse
TeV 2X worse
3600
3400
3200
3000
2800
2600
2400
2200
80
90
100
110
120
130
140
150
160
Weekly Integrated Luminosity, nb-1
Target Stack size mA

Figure 15


4200
4000
3800
3600
3400
3200
3000
2800
2600
80
90
100
110
120
130
140
150
160
"oct21-targetstack"
"oct24-targetstack-95coal"
95% coalescing
70% coalescing
Weekly Integrated Luminosity, nb-1