Booster Throughput

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The available beam power is limited by the beam lost in the tunnel. The Booster is operated by keeping the average beam power lost in the tunnel constant. The beam power lost in the tunnel is equal to the energy lost per pulse times the repetition rate.

$$P_L = J_L R \tag{1}$$

where J_L is the Joules lost per pulse and R is the average repetition rate. As shown in Figure 1, the Booster ran at P_L=440W for the month of September 2005.

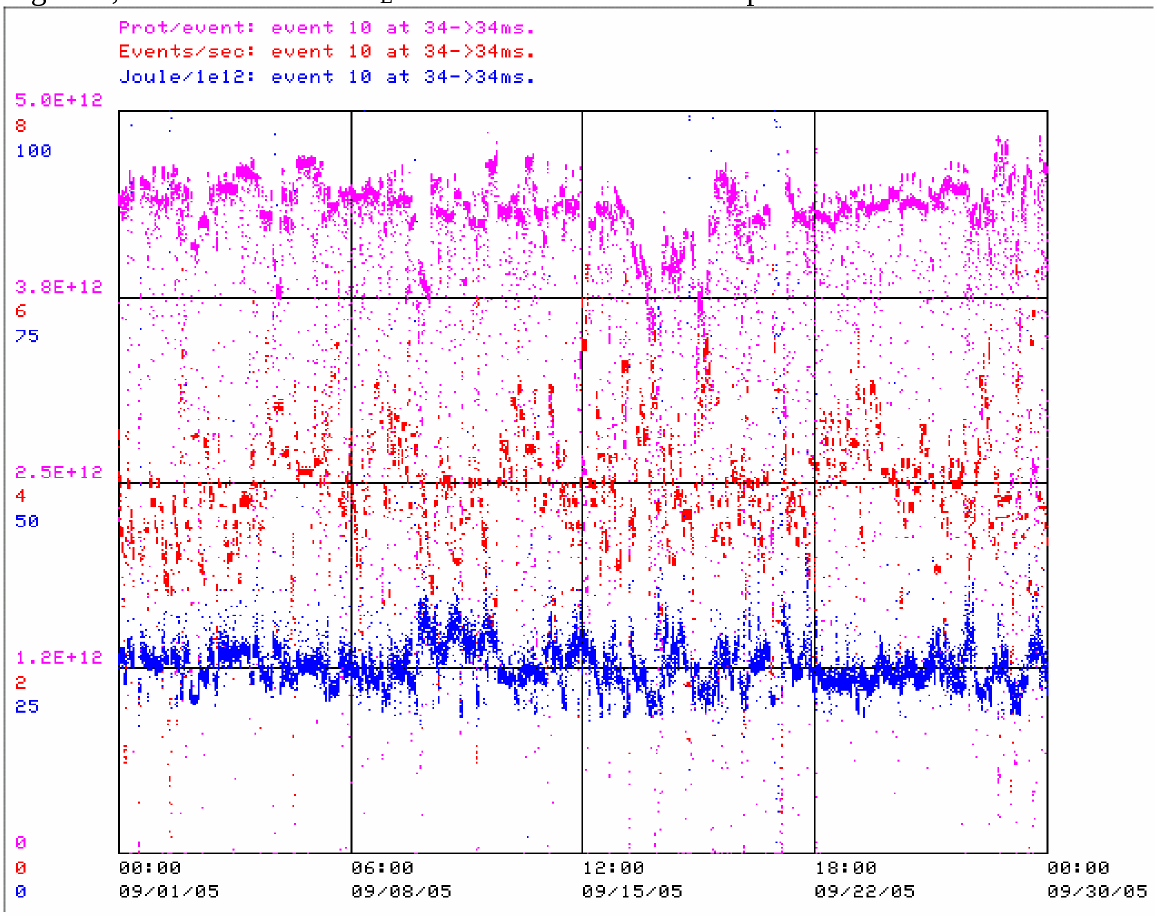

Figure 1. Booster Overall Performance for the September 2005

For simplicity the beam loss can be divided into two categories, beam loss due to creating the beam gap (notch) for extraction and beam lost transversely during acceleration.

$$J_L = E_n \Delta N_n + E_A \Delta N_A \tag{2}$$

where ΔN_n is the amount of beam lost during notching, ΔN_A is the beam loss during acceleration, E_n is kinetic energy when the notch is created, and E_A is the weighted average kinetic energy at which the beam is lost during the acceleration cycle. The energy E_A is a function of the beam loss versus time and is about 1050 MeV for present operations (See Figure 2)

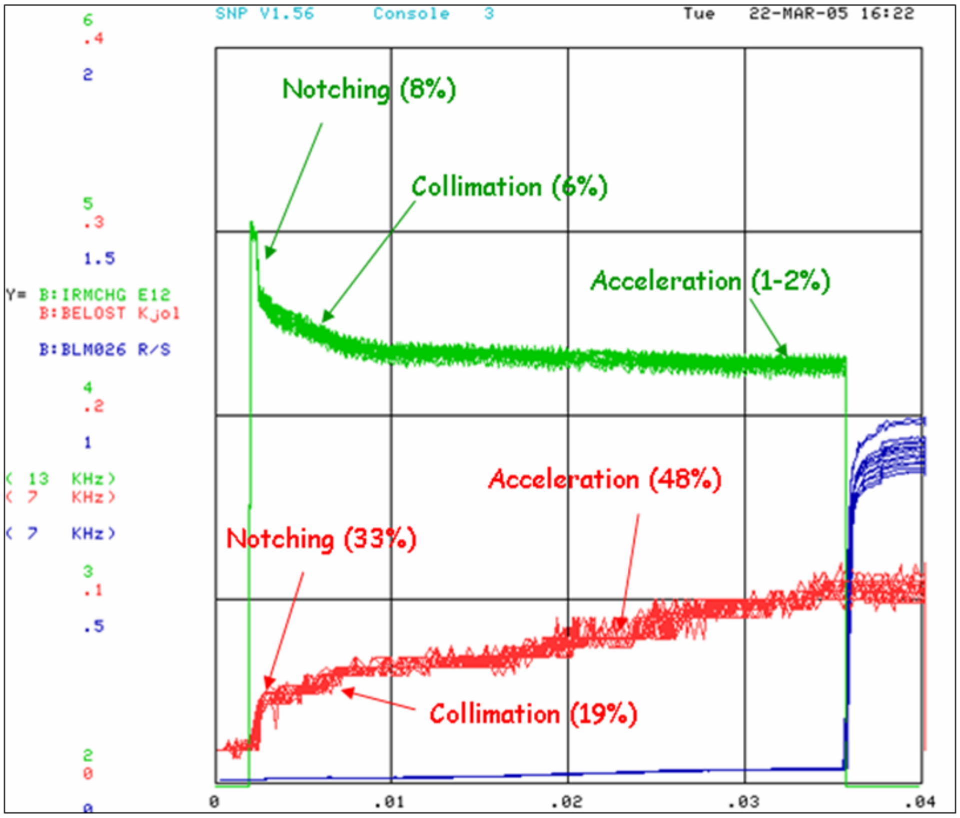

Figure 2 Typical Booster Intensity Profile

The total efficiency of the Booster is:

$$\frac{N_{ext}}{N_{inj}} = \left(1 - f_n - f_A\right) \qquad (3)$$

where f_n is the ratio of the amount of beam loss during notching to the injection intensity and f_A is the ratio of the amount of beam loss during acceleration to the injection intensity. For a given notching fraction, the fraction of beam loss during acceleration that can be tolerated is:

$$f_A = \frac{P_L - \left(N_{ext} E_n R + P_L\right) f_n}{N_{ext} E_A R + P_L} \qquad (4)$$

Assuming a guassian profile as a simple approximation, the amount of beam in the halo that is outside the aperture is:

$$f_h = e^{-3\frac{A}{\varepsilon_{95}}} \qquad (5)$$

where A is the aperture and ε_{95} is the 95% emittance. The amount of beam that is permitted to be in the halo is:

$$f_h = \frac{\Delta N_A}{2\left(N_{ext} + \Delta N_A\right)} = \frac{f_A}{2\left(1 - f_n\right)} \qquad (6)$$

where the factor of 2 comes from the halo in both planes. The aperture required is:

$$A = \frac{S_f\, \varepsilon_{95}}{3} \ln\left(\frac{2\left(1 - f_n\right)}{f_A}\right) \qquad (7)$$

where an extra "safety" factor, S_f, was added.

The magnet misalignment and closed orbit distortion is given as:

$$\Delta x_{align} + \text{c.o.d} = \frac{W}{2} - \sqrt{\frac{A_n}{\beta\gamma}\beta_{max} + \left(\frac{1}{2}\frac{\Delta p}{p} D_{max}\right)^2} + \qquad (8)$$

where W is the width of the magnets, A_n it the normalized acceptance, β_{max} is the maximum lattice beta function, D_{max} is the maximum lattice dispersion function, p is the beam momentum, and Δp is the full width momentum spread.

Booster Aperture Requirements

The procedure is to specify maximum power loss, the extraction intensity, and the average cycle rate. Then using Equation 4, the maximum loss during acceleration is determined. From the acceleration loss, the minimum aperture is found using Equation 7 and the closed orbit tolerance is found using Equation 9. A set of five scenarios for these parameters are shown in Table 1. The scenarios are labeled by the approximate available beam power at 120 GeV. Slip-stacking in the Main Injector will be used to obtain 400kW, slip stacking in the Recycler will be used to obtain 700kW, and momentum stacking in the Accumulator will be used to obtain beam powers greater than 1000kW.

For slip stacking, the Booster must phase align to the downstream machine. Since aligning the Booster will require cogging in the Booster, the notch must be created in the Booster and the loss due to creating this gap must be taken into account. As discussed earlier, this beam loss is rather severe. There are planned improvements to the Booster cogging system in the Proton Plan that will permit the creation of a shorter notch. For momentum stacking, the Accumulator will align to the Booster because there is no beam on the injection orbit of the Accumulator. With no cogging required in the Booster for momentum stacking, the notch will be created at the low energy end of the Linac.

The resulting acceleration efficiency and closed orbit tolerance is shown in Table 2. An aperture safety factor (S_f in Equation 7) of two was used to calculate the minimum injection acceptance. Also, it was assumed that the vertical aperture in the Booster is 1.64 inches for the F magnets and 2.25 inches for D magnets. The horizontal good field aperture is 4.3 inches for F magnets' and 3 inches for D magnets. The RF cavities are located between two D magnets where the horizontal beta function is a minimum and the vertical beta function is a maximum. The aperture of the RF cavities is 2.25 inches. The lattice functions for the F and D magnets are shown in Table 3.

Parameter	Sept. 2005	400kW	700kW	1200kW	1300kW	
Extraction Intensity	4.4	4.7	4.0	4.6	4.6	$x10^{12}$
Rep. Rate	4	8	9	13.5	15	Hz
Average Beam Power Lost	440	440	440	440	440	Watts
Notch Bunches	7	5	5	0	0	
Notch Energy	450	450	450	450	450	MeV
Acceleration Loss Energy	1050	1050	1050	1050	1050	MeV
Norm. Emittance at Inj	10	10	10	10	10	π-mm-mrad

Table 1. Maximum power loss, extraction intensities, and average cycle rates for various scenarios. A normalized injection emittance of 10π-mm-mrad corresponds to a 400MeV space-charge tune shift of 0.25 for an un-bunched beam.

Parameter	Sept. 2005	400kW	700kW	1200kW	1300kW	
Acceleration loss	8.7	3.7	4.0	4.0	3.6	%
Efficiency	83	90	90	96	96	%
Injection Intensity	5.3	5.2	4.5	4.8	4.8	$x10^{12}$
Norm Acceptance at Inj	20.3	26.1	25.8	26.1	26.7	π-mm-mrad
Momentum Acceptance	1.36	1.43	1.43	1.43	1.44	%
Misalignment & c.o.d.	4.1	1.9	2.0	1.9	1.6	mm

Table 2. Efficiency and closed orbit tolerance for various 120 GeV beam power scenarios.

Parameter		
F magnet β_x	33	m
F magnet β_y	14	m
F magnet D_x	3	m
D magnet β_x	14	m
D magnet β_y	22	m
D magnet D_x	2.5	m

Table 3. Booster lattice functions

The Main Injector efficiency, intensity and cycle time for the various 120 GeV beam power scenarios are shown in Table 4. It is assumed that all the loss in the Main Injector due to capturing the large longitudinal emittance of either the slip-stacked or momentum-stacked beam will occur at 8 GeV. This loss is displayed in the last line of Table 4. It was also assumed that there will be more loss for slip stacking than there will be for momentum stacking. The Main Injector intensity for the 700kW scenario was set so that 8 GeV beam loss per unit length in the Main Injector is comparable to the Booster beam loss per unit length. The proton flux for the various 120 GeV beam power scenarios is shown in Table 5.

Parameter	Sept. 2005	400kW	700kW	1200kW	1300kW	
Collider Final Intensity	6.9	8	0	0	0	$x10^{12}$
NUMI Final Intensity	22	40	45	82	82	$x10^{12}$
MI Cycle Time	2.60	2.07	1.33	1.33	1.20	Sec
Collider Batches	2	2	0	0	0	
NUMI Batches	5	9	12	18	18	
Collider 8 GeV Efficiency	88	93	100	100	100	%
NUMI 8 GeV Efficiency	95	93	93	98	98	%
8 GeV Power loss	1068	2237	3252	1607	1785	Watts

Table 4. The Main Injector efficiency, intensity and cycle time for various 120 GeV beam power scenarios.

Parameter	Sept. 2005	400kW	700kW	1200kW	1300kW	
Booster Flux	6.4	13.5	13.1	22.6	25.1	$x10^{16}$/Hr
Collider Flux	1.1	1.5	0.0	0.0	0.0	$x10^{16}$/Hr
NUMI Flux	3.2	7.5	13.1	22.6	25.1	$x10^{16}$/Hr
NUMI Beam Power	162	372	648	1181	1312	kW
MiniBoone Flux	2.1	4.5	0.0	0.0	0.0	$x10^{16}$/Hr

Table 5. Proton flux for various 120 GeV beam power scenarios.