INTENSITY LIMITATIONS IN FERMILAB MAIN INJECTOR

W. Chou, Fermilab,* P.O. Box 500, Batavia, IL 60510, USA

Abstract

The design beam intensity of the FNAL Main Injector (MI) is 3×10^{13} ppp. This paper investigates possible limitations in the intensity upgrade. These include the space charge, transition crossing, microwave instability, coupled bunch instability, resistive wall, beam loading (static and transient), rf power, aperture (physical and dynamic), coalescing, particle losses and radiation shielding, *etc.* It seems that to increase the intensity by a factor of two from the design value is straightforward. Even a factor of five is possible provided that the following measures are to be taken: an rf power upgrade, a γ_t-jump system, longitudinal and transverse feedback systems, rf feedback and feedforward, stopband corrections and local shieldings.

1 INTRODUCTION

High intensity beams are often in demand when proton synchrotrons are operated in fixed target mode or in antiproton or neutrino production mode. In the past half century, scores of proton synchrotrons have been built and tremendous amount of knowledge has been accumulated in their design and operations for understanding where the bottlenecks are and how to conquer them. One of the best examples is Ref. [1], which shows how various measures were taken on the PS Booster at CERN for increasing the beam intensity by an order of magnitude in 15 years. At this moment, the AGS at BNL holds the world record of the highest beam intensity (6.3 $\times 10^{13}$ ppp) in a proton synchrotron.

The design goal of the beam intensity in the Main Injector at Fermilab is modest: 3×10^{13} protons per pulse. But it is by no means the intensity limit. This paper investigates a number of sources that could possibly become bottlenecks. The "Top 10" list is:

- Space charge.
- Microwave instability.
- Coupled bunch instability and resistive wall.
- Beam loading.
- Robinson instability.
- RF power.
- Transition crossing.
- Dynamic and physical aperture.
- Coalescing.
- Particle losses and radiation shielding.

These are in random orders and will be discussed in sequence. They will be re-ordered in the end of the paper to establish a priority list.

Other sources, such as intrabeam scattering and residual gas scattering are considered not to be important. Lattice mismatch, beta-beat and beam steering could be important but it may be more appropriate to study them when machine operation begins.

2 SOURCES OF INTENSITY LIMITATIONS

2.1 Space charge

The space charge may cause emittance growth (especially in the transverse phase space) and particle losses (from resonances). When the space charge limit is reached, the transverse emittance would grow as bunch intensity increases, while keeping their ratio a constant. The characteristic parameter is the Laslett tune shift, which comes from both the space charge and image charge. In the Main Injector, it is -0.08 at 6×10^{10} protons per bunch at injection. It would become -0.4 if the beam intensity is increased by a factor of five, assuming the same transverse emittance. Such a big tune shift would cross a number of resonance lines. A standard way to cure it is to employ stopband corrections, which have been successful in many machines, including the AGS.

2.2 Microwave instability

Table 1 is the impedance budget of the Main Injector. The total longitudinal $Z_{\|}$/n is 1.6 Ω, the total transverse $Z_{\perp}$ is 2.2 MΩ/m. The threshold of microwave instability and transverse mode coupling instability is also listed in the table. It is seen there is a safety margin of 4-5. When the intensity is increased by a factor of 5, one might see transverse mode coupling, which, however, has never been observed in any proton machine. A possible solution to push the intensity even higher is by intentional blow up of the longitudinal emittance, which has been used at CERN for years.

2.3 Coupled bunch instability and resistive wall

The 18 rf cavities in the Main Ring (MR) will be re-used in the Main Injector. The longitudinal coupled bunch instability driven by the higher order modes (HOM) in these cavities have been observed in the MR. At present there are two narrow-band passive dampers for the modes 128 and 225 MHz. It is not clear which modes would be dangerous when these cavities move to the MI. The calculation shows the growth time at nominal intensity is about 10 ms in the MI, which can be damped by active feedback. As beam intensity increases by a factor of 5, the growth time would de-

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Table 1. Main Injector Impedance Budget

Component	Number	Impedance	
		$Z_{\parallel}/n$ (Ω)	$Z_{\perp}$ (MΩ/m)
RF cavities (HOM)		0.09	0.023
Main cavities (53 MHz)	18		
Coalescing (2.5 MHz)	5		
Coalescing (5 MHz)	1		
2nd harmonic (106 MHz)	1		
Transitions (tapered)		0.012	0.01
RF section	10		
Inj section	2		
Bellows (shielded)	552	0.37	0.67
Flange gaps (shielded)	552	-	-
Weldments	2208	0.001	0.005
Gate valves (shielded)	34	0.04	0.05
Pump ports (screened)	577	0.1	0.07
Beam position monitors	208	0.18	0.3
Kickers		0.3	0.6
p inj (1.1 m)	3		
$\bar{p}$ inj/p extr (2.24 m)	2		
$\bar{p}$ extr (2.2 m)	2		
Abort (2.2 m)	2		
Lambertson laminations		0.1	0.3
Lambertson joints		0.3	0.1
Lambertson-quad	12		
Lambertson-Lambertson	6		
Lambertson-dipole tube	10		
Resistive wall		0.11	0.092
Total		1.6	2.2
Instability threshold:			
At 8.9 GeV/c		39	7.9
At 120 GeV/c		8.0	16

crease by a similar portion, which makes the feedback more demanding. Hence, it is desirable to install a wide-band passive damper in the cavity to damp all the HOM above certain frequency, say, 200 MHz. A new version of the simulation code MAFIA, v.4, allows its frequency domain solver to deal with lossy materials such as ferrite. This can be a useful tool in the investigation of such a damper.

The resistive wall instability has a much faster growth time, about 1.2 ms at 3×10^{13}, which is about 100 turns. The specification of the transverse feedback has a damping time of 20 turns. Therefore, it should be able to handle higher beam intensity.

2.4 *Beam loading*

The transient beam loading gives a phase modulation due to the gap in the bunch train. The worst case is when there is only one batch in the machine. In this case the phase modulation is about 20°. Another beam loading effect is the instability driven by the fundamental mode of the cavity due to detuning. Although calculation shows it would not happen in the MI because of its high revolution frequency (90 kHz), the observation of such kind of instability in the MR even in the Booster causes concern. Presently mode dampers are used. There is also a plan to build fast rf feedback to suppress it. But the power amplifier needs to work in the linear region (class A or AB) for this purpose. The current Fermilab amplifier is class C. Modification is thus needed.

2.5 *Robinson instability*

The first type Robinson instability is rarely seen in proton machines thanks to their low synchrotron frequency. The second type, however, could occur at high intensities when the relative beam loading factor exceeds 2. The value of this parameter in the MI is 1.4 at nominal intensity. It would cross the threshold even with a moderate intensity upgrade. Therefore, fast rf feedback (or feedforward) is also necessary in this respect.

2.6 *RF power*

The ramp rate in the MI is 260 GeV/s. The total rf power is 3.6 MW. Therefore, the maximum number of protons that can be accelerated at this ramp rate is about 8×10^{13}. This is a hard bottleneck. If one wants to accelerate more protons, then either one needs to purchase more rf power or the ramp rate needs to be reduced.

2.7 Transition crossing

During transition crossing, there could be longitudinal emittance dilution as well as particle losses. Both are observed in the MR. This process is complicated and involves several mechanisms: nonlinear effect, bunch length mismatch due to space charge, scraping due to limited momentum acceptance, microwave and negative mass instabilities, *etc.* This problem will not be as severe in the MI as in the MR, because the MI has higher ramp rate, lower $Z_{\|}$/n, smaller emittance and larger momentum acceptance. However, during intensity upgrade, transition crossing could become a critical point. Therefore, a conceptual design of a γ_t-jump system is being worked out.[2] The plan is to implement it at high intensity operations.

2.8 Dynamic and physical aperture

The sagitta and good field quality of the MI magnets result in large dynamic aperture. The required dynamic aperture is 40π mm-mrad. The tracking shows it is as big as 120 π. Therefore, there should be no problem in dynamic aperture.

However, there are certain areas in the ring where the physical aperture is noticeably small, in particular, in the MI52 region. It is the injection point of 8 GeV antiprotons and extraction point of 120 and 150 GeV protons. It is conceivable that this area would be a radiation hot spot due to large amount of particle losses. Possible solutions include the use of large aperture quadrupoles, local shielding and careful beam steering.

2.9 Coalescing

The main concern is the microwave instability that could develop during adiabatic debunching, when the bunch length σ_b becomes longer while the energy spread σ_p becomes smaller. According to the Keil-Schnell criterion, the instability threshold goes linearly with σ_b but quadratically with σ_p. Therefore, the threshold would be lower. As a matter of fact, if the minimum full bunch height is 12 MeV during debunching, the impedance threshold would be as low as 1 Ω even at nominal intensity (6×10^{10} per bunch). More study needs to be done on this subject. More rf voltage will certainly help, because it allows larger longitudinal emittance.

2.10 Particle losses and radiation shielding

The DOE regulation gives a upper limit of annual operational losses, which is 1.0×10^{19} at 8 GeV and 0.41×10^{19} at 120 GeV. At the nominal intensity of 3×10^{13} ppp, 10% loss rate would mean 5×10^{15} particle losses per hour. Thus, the annual operation time would be limited to 2000 hours. If the beam intensity goes up by a factor of 5 but the loss rate is still 10%, then the allowed machine operation time will be reduced to 400 hours. Therefore, one must keep the loss under control during the intensity upgrade.

3 CONCLUSIONS

When the beam intensity goes beyond the design value of the beam intensity in the MI, the potential bottlenecks would likely appear in the following order. The possible solutions are given in the parenthesis.

1. RF power. (Needs money to purchase more power.)
2. Transition crossing. (γ_t-jump)
3. Instabilities and coalescing. (Low machine impedance, passive and active dampers)
4. Beam loading and Robinson instability. (Fast rf feedback and feedforward)
5. Space charge. (Stopband correction)
6. Physical aperture limit at MI52 and the associated particle loss and radiation shielding problem. (Large aperture quads, local shielding, careful beam steering)

As a conclusion, it seems to increase the MI beam intensity from 3×10^{13} by a factor of 2 is straightforward, provided that the Booster is capable to deliver twice as many protons to the MI (which may require multi-turn injection from the Booster by use of slip stacking or other techniques). A upgrade by a factor of 5 is also possible, provided all the measures discussed above would be taken. This would bring the intensity to 1.5×10^{14}. Further increase, say, by another factor of 2, would be difficult.

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5 REFERENCES

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