PROJECT X BEAM PHYSICS ISSUES*

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Abstract

Fermilab plans to boost the power of Main Injector beam to about 2 MW by building a new SC 8 GeV linac. Its H^- beam will be strip-injected and accumulated in upgraded Recycler ring, and then transferred to Main Injector for further acceleration to 120 GeV. Beam physics issues related to high intensity operation of Recycler ring and Main Injector are considered.

NEW INJECTOR

The present high energy physics program in Fermilab is based on the successful operation of the injector complex consisting of 400 MeV Linac and 8 GeV Booster. This complex supports both the Tevatron collider operation and the neutrino experiments. It is about 30 years old and its replacement by a modern machine is highly desirable. The collider program will be complete in two years. Therefore the main goal of the new injector complex is to support high power operation of the Main Injector (MI) for the continuing 120 GeV neutrino program as well as the 8 GeV program focused on low energy neutrino and muon beams [1]. It is expected that the average power of the 120 GeV MI beam on the target will grow from 0.35 to 2.3 MW.

Table 1: Parameters of the linac

	ILC linac	SC linac
Beam current, mA	9	21
Pulse length, ms	1	1.2
Repetition rate	5	10
Average power, MW	0.36	2
Accelerating gradient, MV/m	31.5	25

Presently, the preferred solution is based on a SC linac built on technology developed for the ILC. Two possible configurations have been considered: an exact copy of ILC linac and a SC linac based on the ILC technology but modified to better satisfy the existing and future Fermilab infrastructure. In this document they are called "ILC linac" and "SC linac", respectively. Preliminary parameters of such linacs are presented in Table 1. The linac accelerates an H^- beam which is then injected into the ring with the strip injection. Because of the limited power of the ILC based linac, three linac pulses are required to fill the MI. To minimize the time that the MI sits at the injection energy, the existing Recycler ring is utilized. In this case 3 consecutive linac pulses are stored in the Recycler, and then the beam is immediately transferred to MI. The second choice of the SC linac allows one to fill MI during a single pulse. Such a choice does not require the Recycler for intermediate storage of the beam.

The injection complex described above together with the MI upgrade required to achieve 2 MW operation has been called Project X. No final decisions about the linac configuration have been taken but the momentum at the present time is toward a specialized CS linac. This paper is devoted to a discussion of MI parameters as well as its beam physics issues and limitations. The paper is based on a report presented to the Fermilab director in the summer of 2007 [2].

MAIN PARAMETERS OF MI

The main injector upgrade should increase the total beam power by almost an order of magnitude. As one can see from Table 2 this is achieved by a 4-fold increase in the number of particles accelerated in one cycle and shortening the magnetic cycle time from 2.2 s to 1.4 s. The upgrade does not require any significant modifications to the machine magnets or vacuum system. To minimize the machine impedance the existing laminated Lambertson septum magnets must be shielded in a manner similar to that of the Tevatron injection Lambertson magnet [3]. The increased beam power requires a significant upgrade of the existing RF system; and larger beam current requires building more powerful instability dampers.

Direct multi-turn injection of linac beam into the Recycler (or possibly to the MI in the case of the SC linac) with subsequent beam transfer to the MI provides additional advantages in comparison with a circular booster with the same energy as the linac. First, the beam chopping at low energy in the linac allows the possibility of leaving only one abort gap. This would minimize the bunch population for a fixed total number of particles. This is considered to be a main scenario. Nevertheless, if necessary, a special bunch structure can be created by additional chopping of linac beam. It can be helpful for suppression of the electron multipactoring by proton beam and the consequent ep-instability. Second, painting the small emittance of linac beam into transverse and longitudinal Recycler acceptances allows one to minimize the peak particle density. Transverse painting [4] creates a flat density distribution which is quite close to the desired KV-distribution. This reduces the Coulomb tune shifts by factor of ~3 relative to a Gaussian beam with the same 95% emittance. This reduction is taken into account in Table 2 for MI upgrade. The longitudinal painting is performed by an 18 MeV (2.2×10^{-3}) swiping of linac energy during the 1 ms pulse and by chopping the linac beam at the Recycler RF frequency so that 2 of 6 bunches

*Work supported by the US DoE contract No. DE-AC02-07CH11359

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are chopped off. Simulation has predicted the bunching factor to be ~2.2.

Presently, the MI acceptance is limited by extraction Lambertson magnets to about 80 mm mrad. An acceptance of 40 mm mrad is assumed for the upgrade, leaving ~6 mm for steering errors.

Table 2. Main Parameters of Main Injector

	Present	MI upgrade
Injection kinetic energy, GeV	8	
Extraction kinetic energy, GeV	120	
Circumference, m	3319.42	
Revol. frequency at inj., kHz	89.815	
Transition γ, γ_t	21.62	21.62
γ-transition jump, $\Delta\gamma$	-	2
Cycle duration, s	2.2	1.4
Total number of particles	$3.9\cdot 10^{13}$	$1.7\cdot 10^{14}$
Beam current at injection, A	0.56	2.45
Betatron tunes, Qx/Qy	26.42 25.41	26.45 25.46
Norm. 95% emittance, $\varepsilon_x / \varepsilon_y$, μm	15/15	25/25*
Norm. acceptance at inj., μm	40/40	40/40
90% long. emittance, eV s	0.4	0.5
Maximum Coulomb tune shifts, ΔQx/ΔQy	0.033/ 0.038	0.043/ 0.046
Number of bunches	480	548
Number of particles per bunch	$8.5\cdot 10^{10}$	$3.1\cdot 10^{11}$
Betatron tune chromaticity	-10, +10	-20,+20
Beam power on the target, MW	0.35	2.3

The MI upgrade uses the same RF frequency that is presently in use in the MI. To reduce the peak longitudinal density, a second harmonic RF system is used. Its amplitude and phase are chosen to zero the linear and quadratic terms of the RF force in the bunch center:

$$V(\phi,\phi_0)=V\left(\sin(\phi)-\frac{\cos(\phi_0)}{2}\sin\left(2(\phi-\phi_0)\right)-\frac{\sin(\phi_0)}{4}\cos\left(2(\phi-\phi_0)\right)-\frac{3}{4}\sin(\phi_0)\right)_0 \quad , \tag{1}$$

where ϕ is the particle phase and ϕ_0 is the accelerating phase. Such a choice reduces the longitudinal density by ~15%. More importantly, it introduces a large synchrotron tune spread helping to suppress instabilities. Tables 3 and 4 present the main parameters of the first and second harmonic RF systems. Figures 1, 2 and 3 present the MI magnetic cycle and the dependence of RF and beam parameters on the acceleration time. The dependence of RF voltage on time is chosen to keep the bunch as long as possible through entire accelerating cycle. The second harmonic RF flattens the bottom of the potential well and makes the synchrotron frequency equal to zero at zero amplitude. At small amplitudes it grows linearly with amplitude and achieves its maximum at amplitudes of more or about 82% (depending on the accelerating phase) of the bucket size. Figure 3 presents the dependence of this maximum frequency on the acceleration time.

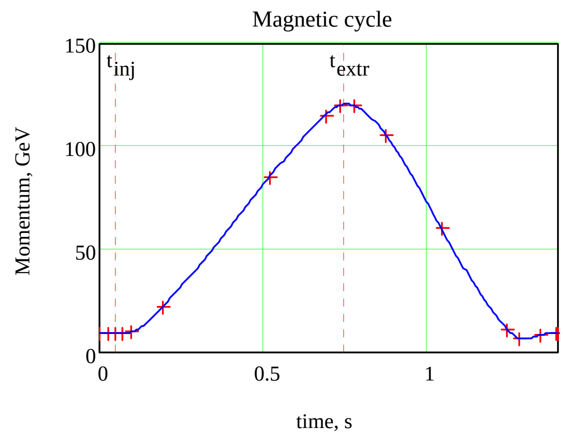


Figure 1. Dependence of beam momentum on time for MI magnetic cycle.

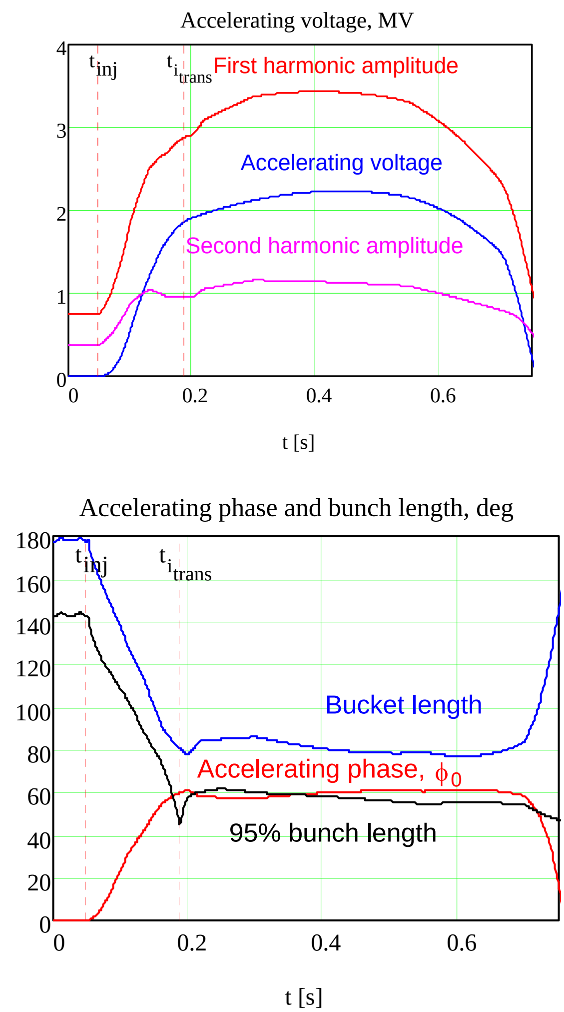
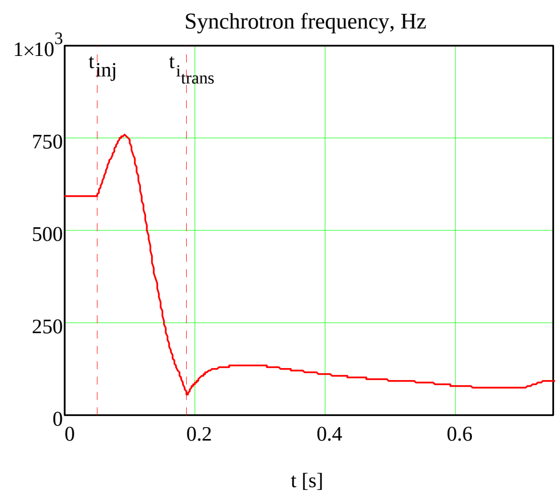


Figure 2. Dependence of accelerating voltage (top) and RF bucket size (bottom) on time.

Figure 3 also presents dependences of the incoherent betatron tune shifts on the acceleration time. They consist of two contributions. The first are the Coulomb tune

* KV distribution is implied

shifts. They are amplitude dependent and therefore cannot be compensated. The second contribution consists of tune shifts due to interaction with the elliptic vacuum chamber and the magnetic cores of dipole magnets (the charge reflection in the vacuum chamber walls and the beam DC current reflections in the cores of dipoles). For ultrarelativistic beam the second contribution practically does not depend on amplitudes of betatron and synchrotron motion and therefore can be corrected by tune offsets proportional to the DC beam current. This is already done for present MI operation. As one can see from Table 2 the flattened distributions and increased emittances allow us to have the Coulomb tune shifts that are only slightly above present values. The chosen values of the Coulomb tune shifts should not present a serious challenge for the future MI operation.



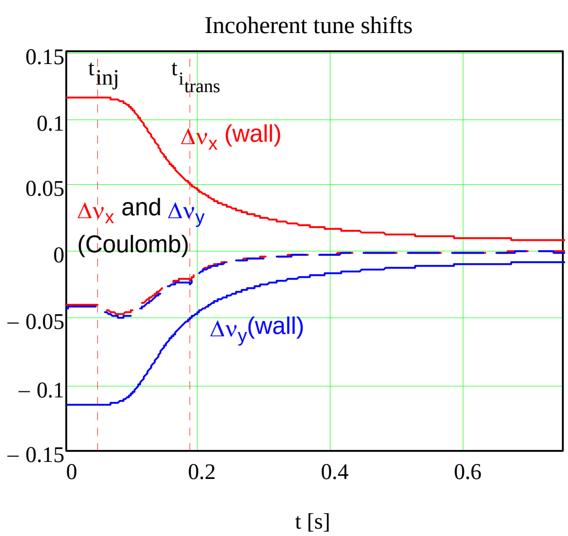


Figure 3. Dependence of synchrotron frequency (top) and betatron tune shifts (bottom) on time.

RF SYSTEM

The peak power transferred to the beam from the RF system is 5.5 MW. As one can see from Eq. (1) the requirement of a flat RF bucket results in that the second harmonic RF system decelerates the beam and consequently requires a larger voltage and power in the fundamental harmonic RF system. However, this is partially compensated by a smaller voltage on the fundamental harmonic system due to larger RF bucket size for the fixed first harmonic voltage. In the scenario presently under consideration, the amplitude and phase of the second RF harmonic are chosen to make the bottom of the potential well flat. In the future we can consider an intermediate scenario where acceleration begins with a flat potential well to minimize space charge effects at the injection, and then the amplitude of the second harmonic is reduced during acceleration. An advantage of such a scheme is that it allows a reduction of the power of the first harmonic RF system. However it would also reduce the margin of beam stability.

Table 3. Parameters of the first harmonic RF system

	Present	MI upgrade
Harmonic number	588	
Frequency swing from injection to extraction, MHz	52.811 - 53.103	
Number of cavities	18	18
Shunt impedance per cavity, (R/Q)*Q, kΩ	500	100
Loaded Q	4000	4000
Peak RF voltage, MV	4.2	4.2
Peak RF power, MW	3.2	13
Average RF power, MW	0.8	5

Table 4. Parameters of the second harmonic RF system

	MI upgrade
Frequency swing from injection to extraction, MHz	105.622 - 106.206
Number of cavities	5
Shunt impedance per cavity, (R/Q)*Q, kΩ	100
Loaded Q	4000
Peak RF voltage, MV	1.2
Peak RF power, MW	1.5
Average RF power, MW	0.9

The number of RF cavities is limited by available space and their total longitudinal impedance. The chosen number of cavities requires RF power sources capable of delivering more than 700 kW/cavity. Fortunately in the 50 - 100 MHz frequency range, two high power tetrodes (EIMAC 8973 and Thales 526) with output powers and plate dissipations in excess of 1 MW are commercially available. Either of these tetrodes could be used in the final amplifier stage and could be driven by one of the existing MI RF power amplifiers. The final amplifier stage would be located in the tunnel as close as possible to a new low R/Q (25 ohm) RF cavity. Depending on the final design parameters for the 2nd harmonic RF system, the Thales TH628 diacrode might be an attractive alternative at the higher frequency.

TRANSITION CROSSING

The γ_t-jump is used to minimize longitudinal and transverse emittance growth excited by transition crossing. The conceptual design of a first order γ_t-jump system consisting of 8 sets of pulsed quadrupole triplets was suggested in Ref. [5]. It provides a $\Delta\gamma_t$ from 1 to -1 within 0.5 ms, i.e. the transition is crossed 20 times faster than with the normal ramp. Note also that the maximum synchrotron frequency at transition is 57 Hz resulting in a 10 deg. synchrotron phase advance during transition.

The design uses a first-order system, making use of the dispersion free straight sections in the MI lattice. Each triplet has two quads in the arc and one of twice the integrated strength in the straight section, with a phase advance of π between each quad. The main advantage of such a design is that the perturbation to the original lattice is localized between the two arc quads.

As one can see from Figure 2, in a γ_t-jump of 2 units the beam never becomes too short. Even at transition the beam space charge longitudinal field is almost 2 orders of magnitude smaller than the RF fields and in the most of cases can be neglected. This should allow transition crossing with no beam loss and negligible longitudinal emittance growth. The simulations were carried out with ESME for a 0.4 eV-sec bunch longitudinal emittance, $3.2 \cdot 10^{11}$ particles per bunch, and zero amplitude in the second harmonic. Without the jump the $\Delta p/p$ reaches 1.2% at transition and exceeds the momentum aperture of the MI. The longitudinal emittance blow-up at transition without the jump is 80% compared to 8% with the jump. Estimates show that including the second harmonic accelerating voltage that was neglected in these simulations makes the transition more adiabatic and less susceptible to the longitudinal instabilities.

COHERENT BEAM STABILITY

In principle, there are two sorts of transverse coherent instabilities in RR and MI: those due to wall resistivity and those due to electron cloud. The γ_t-jump significantly improves the beam stability at the transition. Consequently coherent instabilities will be most pronounced at the injection energy. All essential details of the resistive-wall instability are sufficiently calculable. In contrast, only comparatively rough calculations can be presented for the electron cloud instability [6]. The following means are foreseen to suppress both instabilities: (1) the second RF harmonic, providing high (~100%) spread of the synchrotron tunes; (2) high chromaticity to provide Landau damping, and (3) broad-band dampers.

The resistive wall instability is fastest at the lowest betatron sideband where its growth time is estimated to be about 10 turns. Similar growth time is estimated for the *e-p* instability, assuming 20% charge compensation, evenly distributed within the cylinder of 2.5 cm radius. The most unstable mode for *e-p* instability is estimated at ~10-20 MHz. These fast instabilities cannot be suppressed by chromatic tune spread. Therefore they will be stabilized by bunch-by-bunch dampers. High order instabilities and single bunch instabilities will be suppressed by chromatic tune spread, the value of which should be sufficiently large

$$\sigma_\nu \equiv |\xi| \sigma_p \geq 0.25 \Delta\nu_{SC} \quad . \qquad (2)$$

For the Coulomb tune shift $\Delta\nu_{SC}$=0.05, and the rms momentum spread at injection σ_p=10^{-3} one obtains a required chromaticity above 10.

The multi-bunch longitudinal stability will be supported by a bunch-by-bunch longitudinal damper. Higher order instabilities will be stabilized by the synchrotron tune spread. Taking into account that the voltage induced by the beam in RF cavities exceeds the voltage supplied by RF system, feedforward correction of the RF power and phase will be required to correct voltage errors introduced by the abort gap.

BEAM LOSS AND ITS LOCALIZING

Painting the beam in three degrees of freedom in the Recycler is expected to be extremely helpful in reducing the beam loss in MI. Nevertheless an accurate beam loss estimate is extremely complicated. This multidimensional problem cannot be fully assessed before machine is operational. The following mechanisms contribute to the beam loss during beam operations: scattering on the residual gas atoms, the Touschek effect, loosing beam tails at injection and extraction, beam loss due to instabilities, beam loss excited by non-linear resonances (including resonances excited by the beam space charge), and beam loss due to errors in operations.

For the present MI vacuum of ~10^{-7} Torr the beam loss due to scattering on the residual gas atoms is about $3 \cdot 10^{-4}$ per cycle resulting in a power loss of ~150 W. This is not a negligible number. Consequently, we need to anticipate that in future high power operations the vacuum cannot be worse than what it is at the present. It is expected that at the beginning of high power operations we will have strong multipactoring excited by the beam space charge. This will strongly affect the vacuum, and therefore the vacuum system must have enough capacity to take this additional load.

Beam loss due to intrabeam scattering and the Touschek effect is expected to be below 10^{-5} and can be neglected.

Machine parameters are chosen to avoid problems with instabilities and non-linear resonances. It is expected that in normal operations they should not make a significant contribution to the beam loss. Multipactoring of electrons and the *ep*-instability related with it are expected to be the major offenders. Successful operation of the B-factories at SLAC and KEK with close positron beam current, bunch frequency, and energy may be the best proof that the problem is solvable. Their experience says that "conditioning" of the vacuum chamber walls is a major remedy. Making such "conditioning" sufficiently fast implies an operation at the maximum power and significant beam loss.

Taking into account the complicated reality of 24 hour machine operation, it would be prudent to expect a beam loss of about 0.1-0.2% resulting in a beam power loss of 1-2 kW. This efficiency is more than an order of magnitude better than the present MI efficiency and it will not be easy to achieve at the beginning of machine operation. The recently installed MI collimation system is capable of intercepting 1.5 kW of beam loss power. More detailed studies are required to understand if this power is adequate or needs to be increased. It is expected that in normal operation this system will be intercepting a major fraction of the beam loss (>99%) leaving the rest of the tunnel comparatively clean.

ACKNOWLEDGEMENTS

This paper is based on Ref. 2 which was prepared by large group of people. The major contributions to the material presented in this paper came from A. Burov, C. Gattuso, I. Kourbanis A. Leveling, L. Vorobiev, A. Valishev, D. Wildman and R. Zwaska. I also would like to thank S. Nagaitsev for discussions devoted to the SC linac and the beam injection to Recycler and S. Werkema for help in the editing of this paper.

REFERENCES

[1] "Second Workshop on Physics with High Intensity Proton Source", January 2008, Fermilab, http://www.fnal.gov/directorate/Longrange/Steering_Public/workshop-physics-2nd.html.

[2] "Accelerator issues of Project X", August 2007, Fermilab, http://projectx.fnal.gov/AACReview/ProjectXAacReport.pdf,.

[3] P.M. Ivanov, et.al., "Landau Damping of the Weak Head-Tail Instability at Tevatron," PAC-2005, p. 2756.

[4] D. Johnson, et.al., "An 8 GeV H^- multi-turn injection system for the Fermilab Main Injector, PAC-2007.

[5] W. Chou, et. al., "Design of a gamma-t-Jump System for Fermilab Main Injector", PAC-1997, Vancouver, Canada.

[6] M. Furman, "Electron-Cloud Build-up simulations for FNAL Main Injector", this conference.