STATUS OF THE PROTON DRIVER STUDY AT FERMILAB

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Abstract

In order to enhance Fermilab hadron research program and to provide a proton source to a future muon storage ring or a muon collider, the study of a new high intensity proton machine called the Proton Driver is being pursued at Fermilab. It would replace the present linac and 8 GeV Booster and produce 20 times the proton intensity as the Booster. This paper gives a status report on a number of design issues of this machine.

1 INTRODUCTION

In the summer of 1997, a group of people at Fermilab led by S. Holmes launched a study for designing a new proton source that would replace the present booster. The goal was to increase the proton intensity by a factor of 20. The results are documented in Ref.[1], which describes the basic features of such a machine. Since November 1998, a design team has been formed. Its task is to complete a Technical Design Report (TDR) by the end of FY2000. This paper reports the status of the TDR work.

This is a dual-purpose machine. On the one hand, it could serve as an intense proton source of a future muon collider or a muon storage ring. On the other hand, it would also enhance Fermilab hadron research program. This machine shares a number of common features with other high intensity proton machines (SNS, ESS and JHF), such as large number of protons per cycle, rapid cycling and high beam power. However, the proton driver has a unique feature. Namely, it must keep the longitudinal emittance small so that at exit the bunch is short.

The proton driver consists of three new machines: a 1 GeV linac, a 3 GeV pre-booster and a 16 GeV booster. The design goals are: 1×10^{14} protons per cycle, 15 Hz rep rate, an rms bunch length 1-2 ns at exit. The construction of these new machines would be staged. In Phase I, a new 16 GeV booster would be built in a new tunnel. The present 400 MeV linac will be used as its injector. In this Phase, the proton intensity could reach 1/4 of the design goal, *i.e.,* 2.5×10^{13} per cycle. Then, in Phase II, a new linac and a pre-booster would be built to reach the design intensity. There are several reasons for taking this approach. (1) Phase I is a logical step in proton intensity upgrade. The present booster can only deliver 5×10^{12} protons per cycle, which is limited by the machine acceptance and radiation shielding. The present 400 MeV linac, on the other hand, can deliver 2.5×10^{13} H$^-$ particles. The newly constructed Main Injector (MI), with certain upgrades, is also

believed to be able to take 2.5×10^{13} protons from a booster batch. Thus, a new booster will remove the bottleneck and keep the linac-booster-MI operation in balance. (2) This approach gives the least disruption to the HEP experiments. (3) It also has immediate benefits to the existing program (NUMI, KAMI, MiniBooNE and long term collider experiments).

Table 1: Parameters

Stage	Phase I	Phase II
Machine	New booster	New linac & pre-booster
N (per cycle)	2.5×10^{13}	1×10^{14}
Rep rate (Hz)	15	15
E_{inj} (GeV)	0.4	1 (pre-boo), 3 (booster)
E_{max} (GeV)	16	16
P (MW)	1	4
f_{rf} (MHz)	53	7.5

2 BEAM PHYSICS

2.1 Longitudinal dynamics

One of the most demanding design parameters is the particle density in the longitudinal phase space. At 7.5 MHz, each bunch contains 2.5×10^{13} particles with an emittance $\epsilon_L = 2$ eV-s. This density is several times higher than that in most existing synchrotrons (except the ISIS, which operates at 2.1×10^{13} per eV-s). Therefore, longitudinal emittance preservation is essential, and the conventional "trick" of intentional ϵ_L blow-up for suppressing instabilities would not be applicable.

When such a high density proton beam is injected into the MI, it would create additional problems. The MI uses a 53 MHz rf system. The frequency is 7 times higher than the proton driver (7.5 MHz). This implies that only one out of every 7 buckets in the MI will contain particles. The number of protons in each bucket would be 2×10^{12}, which is 35 times higher than its present value (6×10^{10}). Thus the transition crossing could be a severe problem. Indeed, simulations show large particle losses at such a high bunch intensity. Fortunately, there are two methods that can effectively solve this problem: (1) A γ_t-jump system has been designed for the MI. It can provide a $\Delta\gamma_t$ from +1 to –1 within 0.5 ms. (2) An inductive insert can compensate the space charge impedance. When these measures are added in the simulations, the particle loss is reduced to zero and the emittance growth becomes moderate (20%).

2.2 Beam instability and space charge

There are several open questions on this subject. (1) Is there any microwave instability below transition? The Keil-Schnell criterion shows no discrimination against cases either above or below transition. But in the real world, while numerous machines have reported microwave and negative mass instabilities above transition, none of them (to the author's knowledge) has seen these below transition. The capacitive space charge impedance certainly helps keep beam stable below transition. But whether a big resistive impedance could drive beam unstable remains to be seen. (2) Is there any fast head-tail instability in a proton machine? This type of instability is clearly observed in electron machines but has never been seen in any proton machine. A recent paper[2] claims the space charge would make the mode coupling more difficult, thus suppress this instability. This topic deserves more investigation.

To keep the incoherent space charge tune shift under control, the normal measures (higher injection energy, larger transverse emittance, painting, 2nd harmonic rf) will be taken. A large dispersion (± 15 m) lattice in the pre-booster is also under consideration, which could lower the Laslett tune shift by enlarging the horizontal beam size. There is a speculation that it is the coherent tune shift caused by the space charge, not the incoherent one, that actually hurts the beam. If this is true, then a quadrupole damper could help. This is a research topic at several labs (*e.g.,* KEK and GSI),

2.3 Lattice design

The new booster size will be the same as the present booster (474 m). A primary reason for this choice is that it matches the size of the $\bar{p}$ Accumulator. The pre-booster is a third of the booster size (158 m). Two lattices are under study – FODO and FMC (flexible momentum compaction). Both must give a γ_t larger than the extraction energy to avoid transition crossing. The FODO is possible for the pre-booster but difficult for the booster because of the scaling $\gamma_t \sim \sqrt{R}$. The FMC is more flexible but generates large β-function swing, which could be a source of halo formation. A difficulty experienced in the lattice design is the needed utility region for rf, injection and extraction. It is hard to place all these in dispersion free sections due to the compact machine size. A compromise is to put rf in the short free space, where the dispersion could be large (~ 2 m). Then, one needs to understand the synchro-betatron coupling problem. Existing literatures (*e.g.,* Ref.[3]) has studied integer resonances ($k\nu_\beta \pm m\nu_s = n$ with $k = 1$) and provided a solution. Work is needed for general cases ($k = 2, 3, ..$). The H^- injection region has low β in both planes. The x-plane painting is achieved by using 4 slow bump magnets (for orbit bump) and 2 fast bump magnets (for painting), the y-plane painting by a steering magnet (varying y'). The dependence of temperature rise and emittance growth on the foil thickness is being calculated.

2.4 Beam losses

There is a widely quoted number, 1 W/m, for tolerable beam losses in the "quiet area." But this number needs to be checked. Using the preliminary lattice and magnet design of the proton driver, MARS calculation shows that 13 W/m can be tolerated for hands-on maintenance. (After 30-day irradiation and 1-day cooling, the residual dose at contact is less than 10 mrem/hr.) This means the tolerable beam loss can be an order of magnitude higher than what was previously believed. The ground water activation problem gives a somewhat lower limit but can be treated separately. Even if 13 W/m is adopted as the design criterion, beam loss is still a primary concern. A collimation system is necessary.

3 TECHNICAL SYSTEMS

3.1 RF system

There are two rf systems that are under design. In Phase I, the new booster will use a 53 MHz system; in Phase II, both the booster and pre-booster will use 7.5 MHz. The 53 MHz system is a modification of the present booster rf. The 7.5 MHz system is a new one. It uses the Finemet as the magnetic core. There are two advantages of this material: (1) It can stand high B-field (> 5 kG). This means for the same accelerating voltage, the physical length of the rf cavity will be shorter (by 50%). This is important for small machines requiring high rf voltage. (2) It is broadband. So there is no need of tuning. Furthermore, one cavity can provide multiple harmonics (A 50% 2nd harmonic rf is needed for reducing the injection loss). There are also several concerns regarding the Finemet – high power consumption due to low shunt impedance R, and low gap capacitance due to high permeability μ. A radial cut in the core can help raise the Q value and lower R/Q and the effective μ. A prototype 200 kW cavity using five large size cut cores is being built. It will provide 20 kV at 7.5 MHz. This work is in collaboration with the KEK and is part of the US-Japan accord.

The challenges to the beamloading compensation system are: (1) high beam intensity (16 μC); (2) short beam pulse at exit (a few ns); (3) low Q of the rf cavity (which means the beamloading voltage has a rich Fourier spectrum). Several compensation methods are under study: feedforward, direct rf feedback and cathode follower. It is planned to set up an rf test station for high power rf test and for bench test of the beamloading compensation.

3.2 Magnet and power supply

The magnet has large aperture (5" $\times$ 10") and will use thin silicon steel laminations. The peak field is chosen to be 1.3 T to avoid saturation. The requirements on the end design are: (1) minimizing eddy current heating; (2) making uniform effective length in the end region; (3) minimizing harmonics. The ac loss data from the vendor's catalog are not directly applicable, because they are not measured at 15 Hz and have no dc bias. An ac loss measurement fa-

cility is being set up. A study was done to compare programmable with resonant power supply systems. Although the former has advantages, it is ruled out for two reasons: (1) Its cost is several times higher than the latter; (2) There is no existing solution for storage of large reactive power (about 400 MVA) at 15 Hz. Three different resonant systems are being studied: (a) A single resonance system at 15 Hz; (b) A dual-resonance system: 15 Hz plus a 12.5% 30 Hz component; (c) A dual-frequency system with a switch: up-ramp at 10 Hz, down-ramp at 30 Hz. The cost difference among the three systems is within 20%. The main advantage of (b) and (c) is the potential saving in rf power (about 25-33%). Simulation models for each circuit have been established. It seems there is no show stopper in either (a) or (b). The concern about (c) is the ripple effects at injection when the switch is turned off. An accurate estimate of the stray inductance and capacitance in a real system is crucial in this analysis. When a resonant power supply drives separate functioned magnets, tracking between dipoles and quads is a problem. One solution is to put the main dipoles and quads on the same bus, while using trim quads for tuning.

3.3 Vacuum pipe

There are two options for the beam pipe. One is a ceramic pipe with an rf shield inside, as used at the ISIS. This design works well. The shortcoming is the additional aperture it would take (about 1.5 - 2 inches), which makes the magnet more costly. The other option is a thin Inconel pipe. Because of its high strength and electrical resistivity, the eddy current heating of Inconel is about 1/4 of that of stainless steel. But still, the heating would reach about 3 kW/m, which must be removed by a cooling system. A prototype large aperture (5" $\times$ 8") thin (0.05") Inconel pipe with water cooling is being designed and fabricated. The eddy current induced field error is a few tenths of a percent, which may require correction elements.

3.4 Collimation system

A collimation system is crucial for localizing beam losses. This system is integrated in the early stage of the lattice design so that its location can be optimized. A preliminary collimator system has been designed and STRUCT tracking shows that more than 99% of the lost particles can be captured. It is a 2-stage system, consisting of a 3-mm thick primary collimator (graphite) and four 1.5-m thick secondaries (iron). Assuming 10% particle losses at 3 GeV, it gives 72 kW. This system can capture most of the lost particles and leave only about 480 W outside the collimator region. Thus, in the "quiet area", the loss will be below 10 W/m.

3.5 H^- source and linac

The present H^- source can deliver 50 mA, 90 μs pulses through the linac. This is adequate in Phase I, which requires 4000 mA-μs H^- beams. Phase II will call for the development of a new H^- source. The linac will be used in Phase I. At this moment, it is not clear if this linac can also be used in Phase II. To get the answer, two experiments are under way: (1) peak current test, (2) klystron pulse length test. The first experiment has been done by replacing the H^- source by a H^+ source. It shows that about 90 mA can go through the linac with good transmission (70% in the DTL and 95% in the CCL) and reasonable emittance (2.6 π mm-mrad, 90%). The second experiment will use a Boeing modulator and pulse transformer to generate 300 μs pulses to test the klystron. A 6-cell rf cavity will also be tested for its sparking rate at long pulses. An open issue in Phase I is how to chop the beam. Several schemes (ion source chopping, laser chopping, rf chopping, *etc.*) are under investigation. The design work of a new 1 GeV linac will start soon.

4 MACHINE EXPERIMENTS

4.1 Short bunch experiments

Three machine experiments have been performed. One was done at the AGS near the transition; another at the Fermilab booster by rf rotation near the exit. Both used low intensity beams and obtained short bunches. The third one was also done at the AGS but with a high intensity beam (9×10^{12} in one bunch) and at the top porch. The bunch length after the rf rotation is about 1/3 of that before. No adverse effects were observed other than a beamloading problem.

4.2 Inductive compensation experiments

By inserting an inductive component (such as ferrite rings) in the machine, it is expected that certain space charge effects (potential well distortion, negative mass instability above transition) could be reduced. An experiment was done at the PSR. There were evidences that the e-p instability threshold is improved due to a cleaner gap. This experiment will be repeated after the PSR upgrade.

5 ACKNOWLEDGEMENTS

6 REFERENCES

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