RF PARAMETER CURVES FOR A PROTON DRIVER SYNCHROTRON

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1 INTRODUCTION

High average beam power proton synchrotrons in the medium energy range are under consideration at several laboratories for intense and specialized secondary particle sources like muon colliders and ν factories. A 12 – 16 GeV machine with a 15 Hz cycle and $3 \cdot 10^{13}$ p/pulse capability called the Proton Driver (PD) has been studied as a replacement for the Fermilab Booster and as a base for future facilities.[1] A staged development is proposed, initially using 20 modified 53 MHz Booster cavities in 12 GeV operation.[2] A second stage would allow 16 GeV top energy using a 7.5 MHz rf system consisting of 100 15 kV low-Q cavities.[3] This paper discusses the choices of rf system parameters made in the design study. The limited number of existing Booster cavities has led to consideration for stage 1 of an inductive insert in the ring to aid initial beam capture by compensating longitudinal space charge, an admittedly speculative expedient requiring followup with further calculation and some beam experiments. This report is one of nineteen papers at this conference by members of the Proton Driver design team; it relies on these others to help establish the general context.

2 FIRST STAGE (53 MHZ RF)

Stage 1 of the PD serves to replace the present Booster in the Fermilab injector chain and perhaps directly for low energy neutrino production. The top energy is 12 GeV using a lattice designed for 16 GeV capability. It will employ refurbished Booster rf cavities modified to give a 5 inch aperature. The parameters defining rf requirements are collected in Table 1.

The combination of performance demands with the mandated use of a 400 MeV linac injector and modified Booster cavities calls for some unconventional measures. The space charge impedance corresponding to the perfectly conducting wall force is $Z_{\|}/n \approx -230i\Omega$ at injection energy. To control the space charge defocusing, a tunable inductive insert is proposed to cancel this impedance throughout most of the cycle. The insert looks attractive in the modeling; it makes the difference between 96.8 % and 99.97 % for the particle transmission efficiency for the complete cycle. The idea is not new;[4] it has been tried in two different machines.[5, 6] However, studies have not been carried out over a wide range of beam energy, momentum spread, *etc.*, and more are needed.

The magnet ramp is driven by a 15 Hz resonant supply plus an independant second harmonic supply that is adjusted in phase and amplitude to minimize the required peak rf voltage. The parameter optimization is driven primarily by the effort to minimize beam loss. Because the rf voltage limit is so strigent, loss limitation naturally relates closely to longitudinal emittance preservation also.

2.1 Capture and Acceleration

A macroparticle tracking model has been used for the entire cycle from multi-turn injection through matching to Main Injector buckets. The injected protons are taken as a continuous coasting beam at the energy of $B_{\min}$ lasting up to 90 μs timed symmetrically about $B_{\min}$; assymetric timings and energy offsets have not proved helpful. For nominal linac intensity, 70 μs is sufficient to give the required $3 \cdot 10^{13}$ protons, but efficiency does remain good over a longer injection time. The perfectly conducting wall term and the inductive insert are the only sources for the collective potential in these simulations.

The rf voltage is raised linearly during injection from 0 to 65 kV. It is then raised somewhat more slowly to establish a bucket area of 0.064 eVs at 226 μs. Because the slip factor η is large at injection, the particles near $\pm 180°$ of rf phase are all captured in this simple manouver. Certainly some are quite close to the separatrix and subject to later loss, but these losses are practically eliminated by the inductive insert. They could also be controled with a substantially higher rf voltage. After 226 μs, the voltage curve holds the bucket area constant until 4.96 ms where the voltage has reached the design limit of 1.2 MV. It is held at that value until η has dropped sufficiently at about 30 ms to permit reduction. Because of decreasing η and the control of $\dot{B}$ by a second harmonic component in the magnet current, the bucket area scarcely changes until it is allowed to rise at the end of the cycle. Nonetheless, in the absence of the inductive insert there are losses at maximum $\dot{p}$ (about 0.025 s into the cycle). This indicates that the 1.2 MV peak voltage is marginal. $\dot{B}$ reaches zero at 37.93 ms. The voltage required for acceleration alone is 1.09 MV at maximum $\dot{p}$, so there is not much rf focusing. The synchronous phase reaches about $64°$.

The curves for $p(t)$, $\dot{p}(t)$, $V_{\rm rf}(t)$, bucket area $S_B(t)$, and synchrotron tune $\nu_s(t)$ are plotted together in Fig. 1. The curves are normalized to the range between zero and one to display their qualitative interrelation; the magnitudes are indicated by the parametrs in Table 1. Fig. 2 displays the normalized rms emittance, the rms bunch width, and the rms bunch height simillarly normalized.

The apparent effectiveness of an inductive insert and its importance for low loss with the $h = 126$ rf has resulted in its tentative adoption for reducing beam loss and emittance growth. A limited amount of rf focusing is suplemented

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with self-excited focusing voltage. However, the inductance will have a real impedance component which dissipates rf power and could furthermore cause self-trapping instability. Careful studies of the tradeoffs are required to establish net benefit.

The slip factor is so high at injection that the captured beam has energy-phase correlation (bunch tilt) which wastes precious bucket area and causes beam loss. Dividing the rf into two parts on opposite sides of the ring reduces the tilt and resulting loss. Dividing the rf into three equally spaced groups would make a small additional improvement. The planned configuration of the injection, extraction, and collimation systems looks inconsistent with a three-way division.

Table 2 shows the injection-to-extraction transmission efficiency and emittance at extraction for different departures from the optimum modeling result. The top entry is the best result obtained, and each entry following gives the transmission when one condition is changed without attempting to reoptimize the other parameters. Possibly some of the apparently lost efficiency could be recovered in such a reoptimization, but the intention is only to suggest the importance of various conditions to the optimum obtained. The lower final emittance for the more closely grouped cavities reflects directly the removal of bunch halo by having the bunch tilted in the early part of the cycle.

3 SECOND STAGE (7.5 MHZ RF)

In stage 2 the PD is used to produce μ's for a ν factory storage ring. The extraction energy is raised to 16 GeV and the rf system is replaced with an $h = 18$ system to provide the desired bunch spacing. A factor four larger extracted longitudinal emittance is allowed for each of the 18 bunches, so the design brightness is raised by only 65 %. The larger inter-bunch gap permits chopping the linac beam, allowing synchronous injection. The linac beam spans $252°$ of an approximately stationary bucket. There is an additional requirement for $<$ 3 ns rms bunch length at extraction. It can be met by keeping the voltage at 1.4 MV as $\dot{B}$ drops toward the end of the acceleration cycle. The rms bunch length is 0.64 ns with a bunch rotation and 1.55 ns without. The final 95 % emittances are 0.43 eVs and 0.39 eVs respectively. The rf parameters of PD stage 2 are collected in Table 1.

3.1 Stage 2 RF Curves

Because the beam is chopped and there is more adequate rf focusing in stage 2, an inductive insert is not used. There are practically no losses, not only at injection, but throughout the acceleration cycle. The voltage and magnetic ramp curves are similar to those found for stage 1, but the buckets are less full and there is no need for fine tuning of the curves to control losses.

For the narrowest bunches a bunch rotation is intended. However, merely keeping the voltage at its maximum permissable value of 1.4 MV until the end of the cycle gives already an rms bunch length of 1.55 ns, somewhat better than had been anticipated in the initial design. For injection into the Main Injector the final voltage can be set at any convenient value between there and 100 kV or so. Even narrower bunches can be obtained by a quarter period bunch rotation in a mis-matched bucket. The momentum spread becomes wide enough that the contribution of the second and perhaps the third order dependence of path length on momentum are important. These contributions are included in the macroparticle model. Considered but not included here is the effect of path length difference depending on betatron amplitude. Figure 1 shows the phase space distribution of a 0.39 eVs bunch at extraction without rotation in a bucket produced by the maximum 1.4 MV of rf. If a rotation is made, it starts at 37.6 ms when the sychronous phase is $\phi_s = 70°$ and $V_{\rm rf}$ is 145 kV. Fig. 3 shows the phase space distribution; it has an rms emittance of 0.43 eVs and rms length of 0.64 ns.

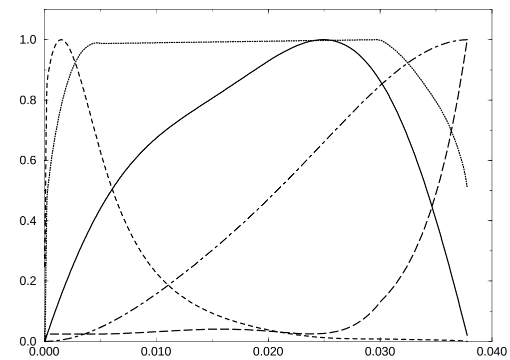

Figure 1: RF parameters durning the cycle of the Stage 1 proton driver scaled to the range 0 to 1: $V_{\rm rf}$ (fine dots), p (dash-dot), $\dot{p}$ (solid), $\nu_{\rm s}$ (short dash), and bucket area (long dash)

4 REFERENCES

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[4] A. M. Sessler and V. G. Vaccaro, "Passive Compensation of Longitudinal Space Charge Effects in Circular Accelerators — The Helical Insert", CERN 68-1, ISR Div. (1968)

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Table 1: Proton Driver rf parameters

General parameters	
injection kinetic energy [MeV]	400
beam intensity [p/cycle]	$3 \cdot 10^{13}$
cycle repetition rate [Hz]	15
circumference/2π [m]	113.21
energy spread at injection [MeV]	± 0.5
momentum compaction	$-1.306 \cdot 10^{-3}$
coefficient of $(\Delta p/p)^2$ in path	$8.252 \cdot 10^{-2}$
coefficient of $(\Delta p/p)^3$ in path	-0.4456
momentum acceptance [%]	2.5
vacuum chamber radius [cm]	6.35
mean beam radius at injection [cm]	4.44
Stage 1 parameters	
extraction kinetic energy [GeV]	12
maximum rf voltage [MV]	1.2
accelerating voltage at $\dot{p}_{\max}$ [MV]	1.09
harmonic number	126
number of populated buckets	119
bunch intensity	$2.5 \cdot 10^{11}$
final rms emittance [eVs]	0.1
Stage 2 parameters	
extraction kinetic energy [GeV]	16
maximum rf voltage [MV]	1.4
accelerating voltage at $\dot{p}_{\max}$ [MV]	1.33
harmonic number	18
bunch intensity	$1.7 \cdot 10^{12}$
final rms emittance [eVs]	0.4
rms bunch length at extraction [ns]	≤ 3

Table 2: Comparison of RMS emittance at extraction and fractional beam loss for optimum stage 1 parameters and cases differing each in a single property

Parameter set	emittance [eVs]	loss [%]
optimum set	0.0197	0.03
rf in two sets	0.0181	0.07
all rf clumped	0.0154	0.21
no inductive insert	0.0247	3.19

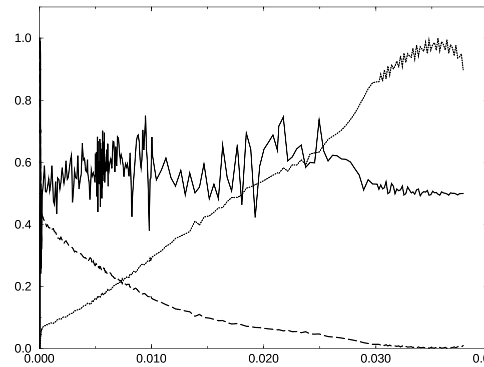

Figure 2: RMS normalized emittance (solid), rms bunch width (dashes), and rms bunch height (fine dots) for the stage one acceleration cycle, all scaled to plot in the range 0 to 1.

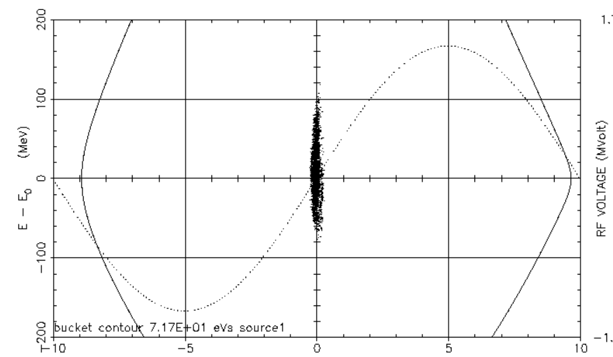

Figure 3: Energy [MeV] *vs.* azimuth [deg] distribution of .43 eVs bunch of $1.7 \cdot 10^{12}$ protons at 16 GeV after quarter period rotation at 1.4 MV, Stage 2 Proton Driver.

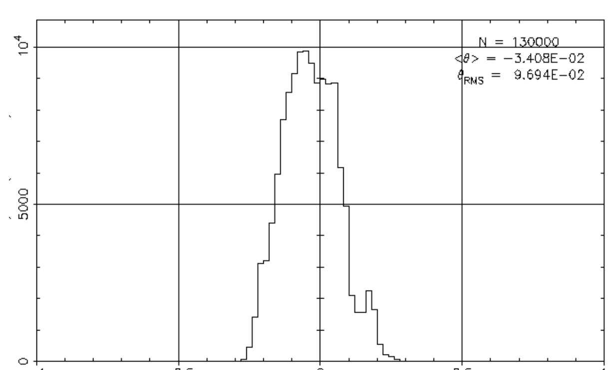

Figure 4: Azimuthal projection of roatated bunch shown in Fig. 3, abcissa in degrees. The rms bunch length in time is 0.64 ns.