THE PROTON DRIVER FOR THE $\mu\mu$ COLLIDER*

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Abstract

The proton driver for the $\mu\mu$ collider might operate at about 15 Hz and produce four bunches of $2.5 \cdot 10^{13}$ protons/bunch at about 10 GeV (or half that number at 20 - 30 GeV) with an rms bunch length of about 1 nsec. A number of options have been considered to produce these bunches using: a) simple bunch rotation, b) energy slewing near γ_t followed by a fast increase of γ_t which facilitates bunching, and c) change of rf frequency in a ring-to-ring transfer. Flexible Momentum Compaction (FMC), or similar, lattices seem to offer control of γ_t even on short time scales. The large momentum spread, space charge tune shift and rapid bunching would tend to stabilize short, intense bunches, although $I_{pk} \sim 1600$ A. Both active (harmonic cavities) and passive (inductive wall) solutions have been considered to minimize high current beam effects. Magnet and vacuum systems would be similar to other high current designs.

1 REQUIREMENTS

The specifications on the proton driver for a $\mu\mu$ collider follow from the muon bunch parameters desired in the collider and from the capabilities of the systems for muon production, collection, cooling, and acceleration. Designs for these systems have been discussed at length in the "Snowmass Book" [1]. Although there is considerable latitude in the choice of system parameters, it is clear that a high-performance muon collider requires a high-performance proton driver. In general, delivery to the production target at a high repetition rate of a few short, intense proton bunches of moderate energy is necessary. The two parameter sets in Table I, adapted from reference [1], typify the formidable requirements on a proton driver for a 2 TeV x 2 TeV collider with luminosity of order 10^{35} cm^{-2}sec^{-1}. Of course the specifications on the proton driver and/or on the other systems can be relaxed for a less demanding collider, such as a demonstration machine at lower energy and luminosity.

Table I. Typical Proton Driver Requirements

Energy	30	10	GeV
Repetition Rate	15	30	Hz
Bunches	4	2	
protons/bunch	$2.5 \cdot 10^{13}$	$5 \cdot 10^{13}$	
Rms bunch length	1	1	nsec

Except for the short bunch lengths, these beam specifications are similar to those for recently designed medium-energy hadron facilities and spallation neutron sources, and so similar approaches are possible. (The short bunch lengths are needed to keep the initial longitudinal emittance of the muons as small as possible, thereby simplifying their collection and subsequent cooling; shorter bunches also allow production of muon beams of higher polarization.) The need for short bunches can be addressed either by adding systems such as a compressor ring or multiple chicanes downstream of the proton acceleration stage(s) or by integrating the short-bunch requirement into the acceleration stage(s). (A companion paper at this conference presents more detail on bunch-shortening strategies.[2])

2 THREE ALTERNATIVES

Three proton driver designs have been considered. The first two columns of Table II show major accelerator parameters of the first two approaches, a 30 GeV synchrotron loosely based on the AGS and a single 10 GeV synchrotron with a 1 GeV linac injector. These two options were described in the "Snowmass Book" [1], and so they will not be discussed further here. This paper presents a third alternative that has been developed since the Snowmass meeting: an 8 GeV, two-ring complex in which the bunch-shortening strategy is integrated into the design of the two synchrotrons. The last two columns of Table II show major accelerator parameters for the two rings of this latter option.

Table II. Major Synchrotron Parameters

Final Energy	30	10	8		GeV
Booster Energy	3.6		4	4	GeV
Injection Energy	0.4	1		1	GeV
Circumference	1080	580	474	158	m
Tune shift	0.1	0.2	0.4	0.4	
Transition energy	40	10-14	14	7	
RF Harmonic	12	8	84	4	
Long Emittance	4.5	2.5	1	0.5	eV-s
Voltage /turn	4	1.8	0.5	0.2	MV

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3 DESIGN OVERVIEW

The design requirements are a challenge for all the accelerators. A design intensity of 10^{14} protons per cycle corresponds to 100 mA x 160 μsec from the linac. Longitudinal tracking including the effects of space charge indicates that efficient capture can be achieved by injecting chopped beam into pre-existing buckets. It is expected that the full energy spread of the 1 GeV H^- injected beam will be reduced to about 1 MeV by a debuncher cavity. Under these conditions the simulations show that the longitudinal emittance per bunch following injection and capture will be about 0.5 eV-s. The small circumference of the first ring helps to keep the longitudinal emittance relatively small.

Transverse space charge effects are serious in both rings. The Laslett incoherent tune shift is limited to the barely tolerable value of 0.4 by the high linac energy of 1 GeV and by large normalized 95% transverse emittances of 200π mm-mrad. In the first ring, the harmonic number of four is chosen to match the desired number of bunches so that every bucket is occupied, thereby keeping the bunching factor favorable to reduce space-charge effects.

The strategy for bunch length reduction calls for a bunch rotation just before extraction from each stage. The rf frequency in the second ring is chosen to be seven times that of the first ring for ease of matching to the longitudinal phase space distribution of the rotated bunch. With a circumference ratio of three, the harmonic number of the second ring is 84; the circumference and harmonic number of the second ring then match those of the Fermilab Booster.

Of course the shorter bunch length exacerbates space-charge effects in the second ring. In fact the transfer energy of 4 GeV is chosen to equalize the Laslett tune shifts shortly after injection in the two rings. After acceleration, another bunch rotation just before extraction from the second ring produces rms bunch lengths of about 1 nsec. Even if the longitudinal emittance has grown by this time to 1 eV-s, the momentum spread after rotation will be only about ±1%, which should be tolerable for a short time in a well-designed lattice.

Transition energies somewhat above the extraction energies are specified for both rings. This not only avoids acceleration through transition but also facilitates the bunch rotation. For the second ring and, if necessary, also the first, flexible momentum compaction lattices [3] can be used to raise the transition energy above the operating range. Such lattices also facilitate rapid variation of the transition energy, as may be useful for some of the bunch-rotation schemes.

4 RF SYSTEMS

In the limited space available, the design is illustrated by a fairly detailed discussion of rf considerations for the critical first ring rather than a more superficial treatment of both rings.

The guide field ramp is resonant at 15 Hz and is linearized by addition of about 15% of second harmonic. The rf frequency varies from 6.64 to 7.43 MHz. The required accelerating voltage $V_{acc} = V \sin \phi_s$ reaches a maximum nearly constant value of 52.7 kV. The rf bucket area is chosen to start at 1 eV-s, twice the expected bunch area, and to grow during acceleration to 1.7 eV-s just prior to extraction. In the case where the beam intensity is sufficiently small so that rf potential well distortion due to beam space charge effects can be ignored, the required rf voltage reaches a maximum value of 104 kV with $\phi_s = 20$ degrees near 8 ms in the cycle. Beyond the maximum, the voltage decreases because the slip factor η decreases as γ approaches γ_t.

At the design intensity, 2.5 x 10^{13} protons per bunch, the rf potential well is distorted seriously by longitudinal space charge effects[4]. In order to develop the required bucket area in the presence of the potential well distortion, the rf voltage must be increased to a maximum value near 146 kV with a corresponding decrease in synchronous phase angle. It may be possible to reduce or eliminate the additional rf requirement by compensating for the space charge induced longitudinal voltage through the introduction into the ring of additional inductance[5.6,7]. This can be done by lining short sections of the beam pipe with ferrite having sufficient bandwidth and relative permeability. The value of the introduced inductance must be reduced during acceleration to compensate for changes in $\beta\gamma^2$. It is proposed to do this by enclosing the ferrite sections in bias current carrying solenoids which are capable of changing the ferrite permeability during acceleration. (A collaboration has been initiated between Fermilab and Los Alamos to make an experimental study of passive compensation of longitudinal beam space charge forces. Several ferrite inductive inserts with bias solenoids are being built at Fermilab. These will be measured electrically at Fermilab and subsequently installed in the Los Alamos Proton Storage Ring for a two day experiment with high intensity beam).

Near 27 ms on the acceleration ramp the rotation period of the ring is about 620 nsec. With 10^{14} protons (16 μC) in the ring the dc current is 26 A. At this point the rf power delivered to the beam, $I_{dc} V \sin \phi_s$, is 1.4 MW. An rf system capable of generating 120 kV and delivering 1.5 MW to the beam over the specified frequency range is indicated. This can be done using ten ferrite loaded rf cavities of standard design. Each rf station (rf cavity, power amplifier, dc power source, etc.) will be capable of generating 12 kV and delivering 150 kW to the beam.

The rf cavities will be single gap double-ended structures slightly more than 1 m long. Each side of the accelerating gap will be driven directly by a 300 kW power tetrode capable of delivering up to 40 A of rf current. Because of the anticipated very heavy beam loading and the consequent large current capability of the tubes (and the relatively low Q of the system), it may not be necessary to actively tune the cavities to (or near) resonance during acceleration. The beam loading will require that the cavities be tuned above the beam frequency in any case, so the cavities may be tuned to a resonant frequency above the maximum beam rf frequency (thus ensuring Robinson stability) and allowed to remain there. This will require that the tubes deliver substantial "quadrature" current in some cases, which will increase the anode dissipation. It is expected that the dissipation and current capability of the tubes to be used will be adequate to meet these demands.

During acceleration the rf bucket area is adjusted adiabatically such that as the bunches approach extraction energy the bunch longitudinal emittance (assumed here to approach 0.75 eV-s) will extend to $\pm\pi/2$ radians in the quasi-stationary buckets. The required bucket height is $\pm$7.1 MeV and the rf voltage is near 2 kV. At this point, just prior to extraction, the rf voltage is raised suddenly to its maximum value, 120 kV. This raises the bucket height to $\pm$75 MeV. The bunch distribution will rotate to a maximum energy spread $\pm$50 MeV in approximately 75 μs. Even with slight deformation due to synchrotron tune spread the resulting bunch length will be within $\pm$7-8 nsec. This will allow extraction and injection into a second ring where the rf frequency may be as high as 53 MHz.

This bunch rotation process may be subject to several limitations. As the momentum spread of the bunches is reduced near extraction the beam conditions may exceed the Keil-Schnell threshold for self bunching instability (microwave instability). Because the beam is below, but near, transition, the growth rate and the resulting longitudinal emittance blow-up may not be sufficient to rule the procedure out. Secondly, as the bunches are narrowed during rotation the longitudinal space charge voltage will increase dramatically and may limit the desired bunch narrowing. This problem may be mitigated by use of the above mentioned passive space charge compensation scheme. Finally, at the end of rotation the beam momentum spread will reach $\pm$1%, so the ring aperture and that of the extraction channel must be made adequate to accept this rather large momentum spread.

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