I. PROTON DRIVER

The overview of the required parameters is followed by a description of possible designs that have been studied in some detail. The section concludes with a discussion of the outstanding open issues.

A. Specifications

The proton driver requirements are determined by the design luminosity of the collider, and the efficiencies of muon collection, cooling, transport and acceleration. The baseline specification is for a 4 - 7 MW, 16 - 30 GeV proton driver, with a repetition rate of 15 Hz and 10^{14} protons per cycle in 2 bunches (for the 100 GeV machine) or 4 bunches (for the higher energies) of 5×10^{13} or 2.5×10^{13} protons respectively. Half the bunches are used to make μ^- and the other for μ^+.

The total beam power is several MW, which is larger than that of existing synchrotrons. However, except for bunch length, these parameters are similar to those of kaon factories [1] and spallation neutron sources [2]. As in those cases, however, the proton driver must have very low losses to permit inexpensive maintenance of components.

The rms bunch length for the protons on target has to be about 1 ns to: 1) reduce the initial longitudinal emittance of muons entering the cooling system and, 2) optimize the separation of the muon populations of + and - polarizations off the target. Although intensities of up to 6×10^{13} protons per cycle have been accelerated, the required peak currents, at extraction, for 1 ns and 4 bunches, is 2000 A which is unprecedented. In the low energy machine, to avoid the even higher current, bunch area requirements, and tune shift constraints, where two bunches of 5×10^{13} are required on target, two bunches can be merged outside the driver. Two bunches would be extracted simultaneously from two different extraction ports, and fed by different transmission lines to the same target. By arranging the path lengths of the two lines appropriately, the time of arrival of the two bunches can be exactly merged. This is explicitly assumed in the FNAL study quoted below.

Since the collection of polarized μ's is inefficient, to do polarized beam physics at the same luminosity, the proton driver should eventually provide an additional factor of approximately two to compensate for the inefficiency in producing these beams.

B. Possible Options

Accelerator designs are site (and to some extent time) dependent, and there have been three studies at three different energies (30, 16 and 24 GeV). In general, if the final energy is higher, the required currents are lower, bunch manipulation and apertures are easier, and the final momentum spread and space charge tune shifts are less. Lowering the final energy gives somewhat more π's/Watt, a lower rf requirement ($V_{rf} \sim E^2$) and perhaps a lower facility cost.

1. A Generic Design

A 7 MW collider driver design based on parameters originally proposed in the Snowmass Feasibility study [3], consists of a 600 MeV Linac, a 3.6 GeV Booster and a 30 GeV driver. Both Linac and Booster are copied from the BNL SNS design [2], using a lower repetition rate and a lower total number of protons per pulse. For the 4 bunch case (2.5×10^{13} protons per bunch), the (95%) bunch area is assumed to be 2 eVs at injection and <4.5 eVs at extraction. The driver lattice is derived from the lattice of the JHF driver using 90 degree FODO cells with missing dipoles in every third FODO cell, allowing a transition energy that is higher than the maximum energy, or perhaps imaginary.

2. FNAL Study

The 4 MW design [4] is described by table II. It is a major upgrade of the present FNAL proton source. The driver lattice would be a Flexible Momentum Compaction (FMC) lattice, which is also used to raise the transition energy or make it imaginary.

The parameters of these two designs are somewhat similar. Both options assume a high transition energy, so that transition does not need to be crossed. The repetition rate of both booster and driver may permit the use of an Inconel vacuum chamber with eddy current correction coils, which would be simpler and less expensive than the ceramic chamber with wires and blocking capacitors used at ISIS.

TABLE I. Baseline proton driver parameters

	Linac	Booster	Driver
Energy range	1 GeV	3 GeV	16 GeV
Rep. Rate	15 Hz	15 Hz	15 Hz
RF voltage per turn		0.15 MV	1.5 MV
Circumference		158 m	474 m
Protons per bunch		2.5×10^{13}	2.5×10^{13}
Beam Emittance [95 %]		200 π mm mrad	240 π mm mrad
Bunch Area [95%]		1.5 eVs	<2.0 eVs
Incoherent tune Shift @ Inj.		0.39	0.39

3. AGS Upgrade

The third study [5] is of an upgrade to the BNL AGS, which should produce bunches larger than those required for the muon collider, but at a lower repetition rate. The AGS presently produces 6×10^{13} protons in eight bunches at 25 GeV and 0.6 Hz. A 2.5 GeV accumulator ring in the AGS tunnel and AGS power supply upgrade to 2.5 Hz operation would match the repetition rate to the 10 Hz repetition rate of the booster. This would generate 1 MW. With an additional upgrade of the linac energy to 600 MeV, an intensity of 2×10^{14} protons per pulse in four bunches of 5×10^{13} at 25 GeV and 2.5 Hz could be reached, raising the power to 2 MW. Other options are also under consideration, such as the addition of a second booster and 5 Hz operation, that would reach the baseline specification of 4 MW.

The AGS momentum acceptance of $\pm 3\%$ required that the longitudinal phase space occupied by one bunch be less than 4.5 eVs. This high bunch density in turn generates stringent demands on the earlier parts of the accelerator cycle. In particular, Landau damping from the beam momentum spread may guard against resistive wall instabilities during injection and longitudinal microwave instabilities after transition. Beam stability can be restored with a more powerful transverse damping system and possibly a new low impedance vacuum chamber. The transverse microwave instability is predicted to occur after transition crossing unless damped by Landau damping from incoherent tune spread or possibly high frequency quadrupoles.

C. Progress and Open Issues

Conventional rf manipulations appear able to produce 1 to 2 ns proton bunches if enough rf voltage to overcome the space charge forces is used and the beam energy is far enough from transition so the final bunch rotation is fast. Both simulations and experimental work have been directed at demonstrating that a short pulse can be produced easily. An experiment at the AGS has shown that bunches with $\sigma \sim 2$ ns can be produced near transition from $\sigma \sim 8$ ns bunches using an rf frequency of 3 MHz (which would be comparable to 1 ns with the 7 MHz systems proposed above) [6]. This experiment was done with bunches of 4×10^{12} protons. Simulations with the ESME code have also shown that 1 - 2 ns bunches of 5×10^{13} can be produced at extraction in a 16 GeV ring with the rf and emittance shown in the table.

The efficiency of capturing and accelerating beam may be increased by compensation of the space charge forces in the proton driver. The use of tunable inductive inserts in the ring vacuum chamber may permit active control and compensation of the longitudinal space charge below transition (since the inductive impedance is the opposite sign from the capacitive space charge) [7]. Initial experiments at the KEK proton synchrotron and Los Alamos PSR with short ferrite inserts appear to show a reduction in the synchrotron oscillation frequency shift caused by space charge and a decrease in the necessary rf voltage to maintain a given bunch intensity [8]. Further experiments are needed to fully demonstrate this technique.

The high rf voltage and beam power and the relatively small size of the machine require high gradient high power rf cavities. There is an agreement between Fermilab, BNL and KEK to collaborate on the research and development of such type of cavities. This work includes the study of magnet alloys and hybrid cavities using both ferrite and new magnet alloys, high power amplifiers and beam loading compensation.

The employment of barrier bucket rf cavities can effectively generate and manipulate a gap in the beam and reduce the space charge effect. Two barrier cavities have been built by BNL and KEK and will be installed on the AGS for test. Another high gradient barrier cavity using magnet alloys is under study at Fermilab.

[1] KAON Factory Study, Accelerator Design Report, TRIUMF, Vancouver, B.C., Canada.
[2] 5 MW Pulsed Spallation Neutron Source, Preconceptual Design Study, BNL-60678, 1994.
[3] Muon Collider Collaboration, in *Proceedings of the 1996 DPF/DPB Summer Study on High-Energy Physics Snowmass'96,* New Directions for High-Energy Physics (Stanford Linear Accelerator Center, Menlo Park, CA, 1997), for updated information, see the Muon Collider Collaboration WEB page at the URL, http://www.cap.bnl.gov/mumu/. See Ref. [9].
[4] C. Ankenbrandt and R. Noble, Presentations at the Workshop on Physics at the First Muon Collider and at the Front End of the Muon Collider, FNAL (unpublishe)., 1997.
[5] M. Blaskiewicz et al., High Intensity Proton Operations at Brookhaven, 1995 Particle Accel. Conf. Dallas, Texas, p. 383, 1995.
[6] C. Ankenbrandt et al., Bunching Near Transition in the AGS, Fermilab Pub-98-006, submitted to Phys. Rev. D.
[7] Z.B. Qian J. E. Griffin, K.Y. Ng and D. Wildman, Experimental Study of Passive Compensation of Space Charge Potential Well Distortion at the Los Alamos National Laboratory Proton Storage Ring, Fermilab Report, FN-661 (1997).
[8] K. Koba et al., 1997, private Communication.
[9] R. B. Palmer A. Sessler and A. Tollestrup, in *Proceedings of the 1996 DPF/DPB Summer Study on High-Energy Physics Snowmass'96,* New Directions for High-Energy Physics (Stanford Linear Accelerator Center, Menlo Park, CA, 1997).