Chapter 3

PROTON SOURCE

Contents

3.1 Requirements

The proton driver requirements are determined by the design luminosity of the collider, and the efficiencies of muon collection, cooling, transport and acceleration. These numbers are shown in Table 3.1. In addition to accelerating a large charge, the machines must operate at high repetition rates, which are determined by the μ lifetime at high energies and the overall power minimization in the accelerator systems. The rms bunch length for protons on target has been set at 1 ns to: 1) minimize the initial longitudinal emittance of μ's entering the cooling system, and 2) optimize the separation of the populations of + and

– polarizations off the target, see Section 11.2.1, and Figure 11.7. Since the collection of polarized μ's is inefficient, we assume the proton driver must eventually provide an additional factor of approximately two to compensate for the inefficiency in producing these beams. An additional requirement is that the proton driver system must have low losses, to permit inexpensive maintenance of components.

Table 3.1: Proton Driver Requirements

	30 GeV	**10 GeV**	
Rep. Rate	15	30	Hz
Protons	10^{14}	10^{14}	/pulse
Bunches	4	2	at target
Protons	2.5×10^{13}	5×10^{13}	/bunch

The proton driver needs to deliver very narrow, high intensity proton bunches for the pion production target. The main requirements for the driver were listed in Tb. 1 in the Introduction. Note that this amounts to 7 MW of beam power in the proton beam. This level of beam power is much higher than what is currently available at proton accelerators. However, many detailed proposals have been worked out for multi-GeV hadron facilities or neutron spallation sources that can achieve similar levels of beam power. For our requirements, the designs for the KAON facility, which is a 30 GeV, 3 MW machine and a combination of the BNL 5 MW spallation neutron source (SNS), and the ANL 10 GeV SNS design are most appropriately used as the starting point for the design of the muon collider proton driver.

Table 3.2: Linac parameters

	$\mu\mu$ **Collider**	**BNL-SNS**	
Max. Energy	0.6	0.6	GeV
Rep. Rate	15	60	Hz
Trans Emittance [95 %]	2.4	2.4	$\pi\ mm\, mrad$
Tot. Energy Spread	2.4	2.4	MeV

There are many ways of achieving the required beam intensities and power, (see Fig 3.1). Tbs. 3.2, 3.3, 3.4 show one possible set of parameters for a proton driver consisting of a 600 MeV linac, a 3.6 GeV Booster and a 30 GeV Driver. Both the Booster and Driver would operate at a repetition rate of 15 Hz with a total of four bunches with 0.25×10^{14} protons per bunch. The relatively low repetition rate of both Booster and Driver makes it possible to use a metallic vacuum chamber with eddy current correction coils.[1] Both Linac

Table 3.3: Booster parameters

	$\mu\mu$ **Collider**	**BNL-SNS**	
Injection Energy	0.6	0.6	GeV
Max. Energy	3.6	3.6	GeV
Rep. Rate	15	30	Hz
Protons per Pulse	1×10^{14}	1.45×10^{14}	
Number of Bunches	4	2	
Circumference	360	360	m
Trans. Emittance [95 %]	260	260	$\pi\ mm\,mrad$
Inc. Tune Shift Inj	0.25	0.25	
rf Voltage per Turn	400	400	kV
rf Frequency (h=4)	2.62-3.24	1.31-1.62	MHz
Long. Emittance [95 %]	2	4	eVs

Table 3.4: Driver Parameters

	$\mu\mu$ **Collider**	**AGS**	**KAON**	
Injection Energy	3.6	1.5	3	GeV
Max. Energy	30	24	30	GeV
Rep. Rate	15	1	10	Hz
Protons per Pulse	1×10^{14}	0.6×10^{14}	0.6×10^{14}	
Number of Bunches	4	8	225	
Circumference	1080	800	1078	m
Transition Gamma	38	8.8	30 i	
Max. Dispersion	2.3 m	2.2 m	7.4 m	
Trans. Emittance [95%]	260	100	100	π mm mrad
Inc. Tune Shift Inj	.10	.10	.10	
RF Voltage per Turn	4	0.4	2.6	MV
Harmonic Number	12	8	225	
RF Frequency	3.24-3.33	2.77-3.00	60.8-62.5	MHz
Long. Emittance [95 %]	< 4.5	4.5	0.2	eVs

and Booster designs are copied from the BNL SNS design[2] with the only difference being a lower repetition rate (15 Hz instead of 30 Hz), and a lower number of protons per pulse (1×10^{14} instead of 1.45×10^{14}). The Driver design is based on the experience with the AGS and on the Japanese hadron Project (JHP)[3] and KAON[4] Driver design. The Driver

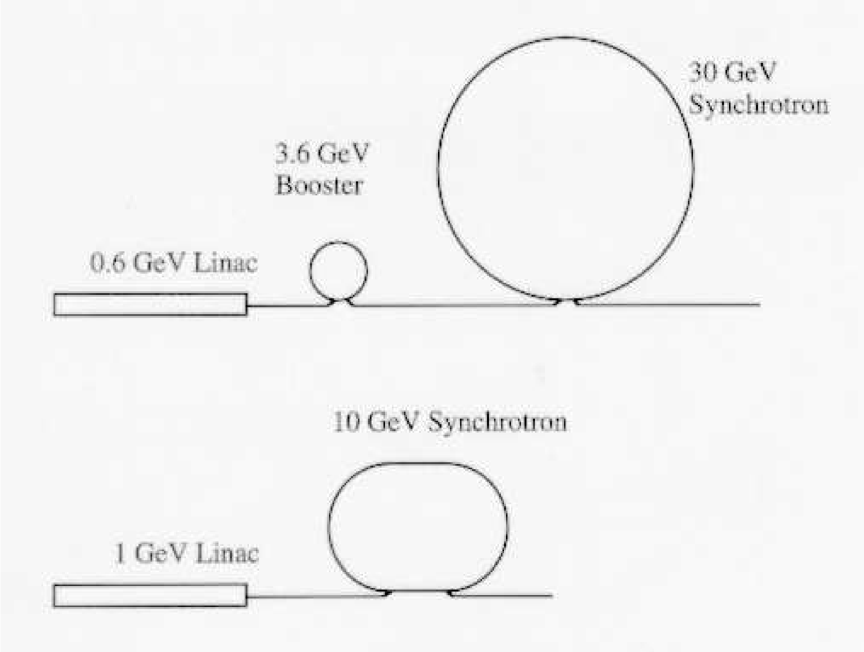

Figure 3.1: Options considered were primarily the simple alternatives of: a) a synchrotron/booster operating at a maximum energy of 30 GeV and, b) a single ring operating at 10 GeV.

lattice is derived from the lattice of the JHP driver using 90 degree FODO cells with missing dipoles in every third FODO cell. Such a lattice allows one to easily achieve a transition energy that is higher than the maximum Driver energy of 30 GeV, or is imaginary, which eliminates the need to cross transition energy but also avoids space charge driven microwave instabilities.

3.2 Production of Short Bunches

There are a number of methods that can be used to generate the short proton pulses required at the pion production target. We list a few that have been considered, either alone or in combination.

1. If the bunches are extracted near transition energy, γ_t, they will have a large $\delta p/p$ and small bunch length. Effects such as longitudinal space charge could be used to compress bunches above transition.

2. RF could be used in a number of ways, for example increasing the voltage will shorten the bunch length, which is proportional to $V^{-1/4}$. Quadrupole modes can be slowly excited in the bunches, and higher frequencies can be used to shorten the overall bucket

length. Bunch rotation should be simpler and faster however. Bunches can be flattened by slowly decreasing the voltage or placing the bunch in the unstable fixed point and then rotated with increased voltage. Bunch rotation can be either a single process, or taken in two steps, with energy shear near γ_t and a separate time shear done further from γ_t.

3. Bunch shortening instabilities, driven by an inductive wall, could be excited by changing the wall impedance, perhaps by unbiasing ferrite.

4. Large numbers of bunches could be coalesced in an internal ring, or low frequency rf linacs, probably induction linacs, can be used to generate a long energy ramp which will coalesce in an external ring or long beam line.

5. Kickers and chicane systems could be used to take a finite number of equal energy proton bunches over different paths to meet at the target.

6. Many short μ bunches could be combined to form a single intense bunch in the μ cooling system.

The simplest option seems to be to extract near γ_t, However it is not clear that the extracted bunches could be made sufficiently short to provide a 1 ns bunch length. Experiments with bunches of 10^{13} protons have been kept circulating for periods of 100 ms with values of $\eta = 0.0005$, with no losses, no negative mass instability, and good agreement with theoretical predictions[5] The negative mass instability was seen in that part of the beam which was above transition, but not in the part of the bucket below transition energy. The stability of unbunched beams near transition has also been studied near transition at the FermiLab antiproton accumulator. [6] Bunching near transition would require that the momentum spread at extraction would be large, however if the final energy of the accelerator is large enough, the fractional momentum spread $\delta p/p$ can, in principle, be accommodated fairly easily at 30 GeV and with some difficulty, at 10 GeV.

Chicane systems can be used to generate a single pulse from a finite number of pulses, however conservation of phase space requires that the bunches cannot be exactly in time and collinear at the exit of such a system. In addition, the total length of chicane beamlines must be roughly $(n - 1/2)$ times the initial maximum separation of bunches.

Bunch Rotation Bunch rotation seems to offer the most reliable procedure for producing short bunches and these methods have been studied in some detail. The longitudinal emittance of the beam, ϵ_L, seems to be more or less independent of injection energy, repetition rate and other parameters for a variety of accelerators, with $\epsilon_L = 1$ eV-s/10^{13} protons, see Table 3.5. In general, the charge/pulse is more closely related to the transverse admittance, and ϵ_L should not be directly related to factors which determine the maximum current limit of the machine.

Table 3.5: Longitudinal Phase Space

	protons/b	ϵ_L **[eV-s]**	**p/eV-s**
IPNS II	1.0×10^{14}	7.5	1.3×10^{13}
BNL-SNS	7.5×10^{13}	4.0	1.8×10^{13}
ISIS(inj)	2.0×10^{13}	2.0	1.0×10^{13}
FNAL	5.0×10^{12}	2.0	2.5×10^{12}
IPNS	3.0×10^{12}	0.4	7.5×10^{12}
KAON	1.5×10^{12}	0.06	2.5×10^{13}
BNL-Booster	1.4×10^{13}	2.0	9.6×10^{12}

Assuming 2.5×10^{13} protons/bunch, this would imply $\epsilon_L = 2.5$ eV-s at injection. When the beam had reached the extraction energy, we require that the bunch length for 4 σ would be 4 ns, however that would imply a momentum spread of 0.06 at 10 GeV and 0.02 at 30 GeV. Although both these numbers are larger than the momentum admittance of most synchrotrons, the debuncher ring of the antiproton source at FermiLab, which operates at 8 GeV, accepts a $\Delta p/p > 0.05$ and contains this beam for a much longer time than the few turns the short, large momentum spread bunch will circulate in the driver synchrotron.

A common feature of many methods is that the bunch compression is a function of the momentum spread $\delta p/p$ and the momentum dependence of path lengths. The time required for this compression is

$$t_b = \frac{\phi_{rf}}{2\pi\, f_{rf}\, \eta\, \delta p/p}, \tag{3.1}$$

and is proportional to the required rf phase change, ϕ_{rf}, and inversely proportional to the rf frequency, f_{rf}, slip factor, η, and the momentum spread, $\delta p/p$. Because of the large currents involved, it is desirable to bunch as quickly as possible to avoid problems with instabilities. Nevertheless coalescence of bunches spread around the circumference might require on the order of 10 - 20 ms in a typical ring. Thus small compressor rings, which could accommodate large η and $\delta p/p$ could be used with induction linacs which would produce a large and linear spread in the energies from front to back in a bunch, or train of bunches.

The bunching time is a function both of the beam energy γ and the difference between the beam and transition energies, $\gamma_t - \gamma$. Because the machine circumference, η and $\delta p/p$

are dependent on the beam momentum, the bunching time goes like p^n, with the exponent n close to 4, depending on the assumptions used to determine the machine circumference and rf frequency. Thus lower energy rings will have much faster bunching times than high energy rings.

Two methods of bunch rotation have been considered. Decreasing the rf voltage to spread the bunch out in time, followed by rotation, can be done for either a single bunch or a number of smaller bunches using a subharmonic, (see Fig. 3.2)[7]. Since the process is nonlinear for large amplitudes, the primary limitation is the initial phase angle which can be rotated into the required bunch length. For an rf frequency of 3 MHz, the maximum rf phase angle is $\sim 45° - 50°$. An alternative method, which requires control of γ_t, is to flat-top the machine at about 1 unit below transition, where synchrotron rotation is slow, then vertically shear the bunch with the linear part of the rf waveform. This is followed by a horizontal shear, done with the transition energy moved further above the beam energy, so the bunch can rotate quickly to a vertical position, (see Figure 3.3)[8]. Nonlinearities also limit this method, since energy variations within the bunch near transition produce variation in η. Nevertheless it seems possible to compensate some nonlinearities by distorting the bunch shape before bunch rotation.

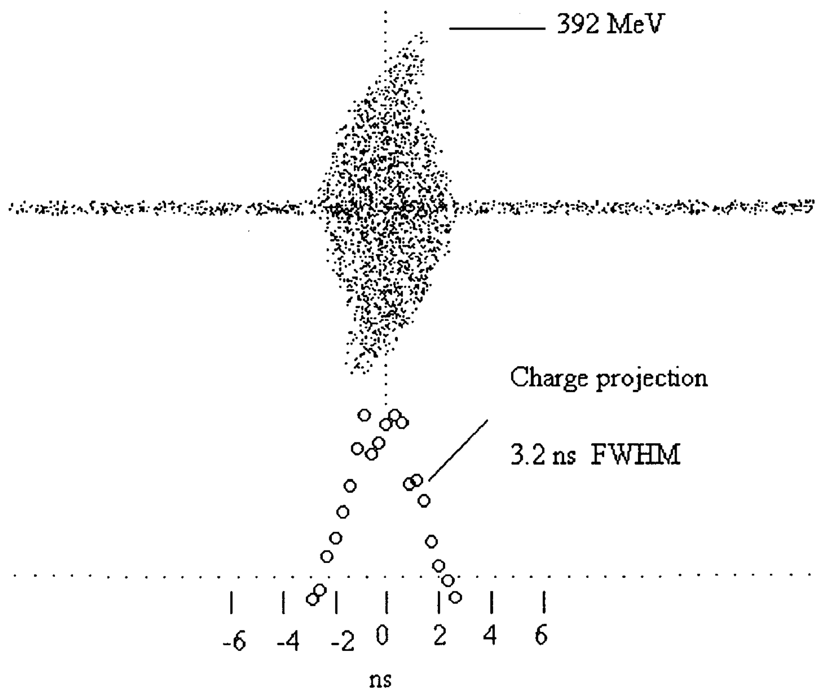

Figure 3.2: Bunch rotation using a 1/4 turn in synchrotron space.

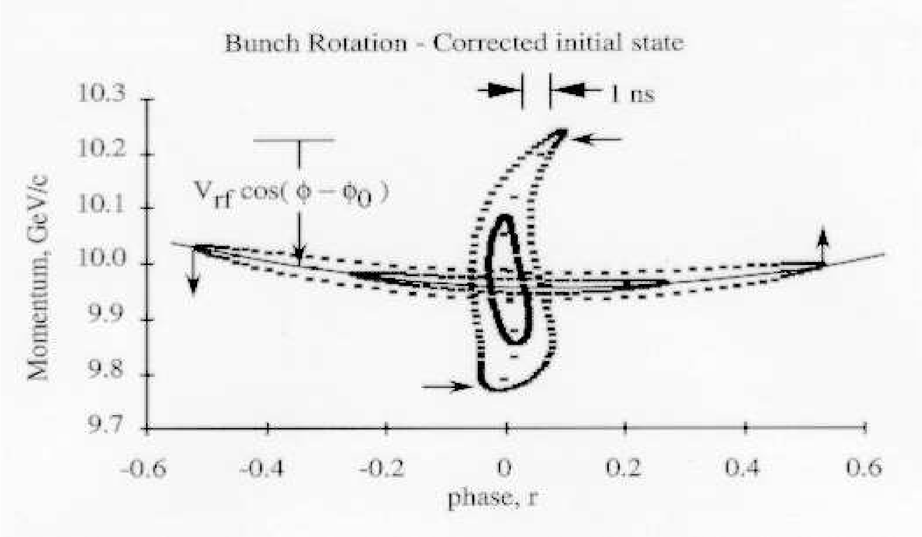

Figure 3.3: Bunch rotation with an energy sheer followed by a rotation in synchrotron space.

Bunch rotation techniques have been demonstrated by Cappi et al. [9] on the CERN PS. In these tests the bunch was rotated by π in longitudinal phase space, giving 2 - 3 times the normal beam current. Since the rotation in longitudinal phase space was by π radians, it was possible to compare the longitudinal emittance before and after the bunch rotation and measure a small, $\sim$1.2, emittance increase. The emittance increase just from bunching alone would presumably be the square root of this value. In order to have control of the transition energy without using high tunes and many quadrupoles and dipoles, we have considered a version of the Flexible Momentum Compaction lattice, suggested by Lee, Ng and Trbojevic.[10] While this lattice can be used to produce imaginary γ_t's, it seems most useful when tuned to produce γ_t values several GeV above the extraction energy. A benefit of this tune seems to be that matching to the zero dispersion straight sections is simple, since the dispersion is naturally close to zero at the ends of the periods. The lattice is also fairly efficient, as it can accommodate a large number of dipoles.

3.3 Stability During Acceleration

Beam in the synchrotron will be subject to instabilities from a number of causes[11]. In general it seems desirable to produce the short bunch for the shortest possible time interval to minimize instabilities. Space charge tune shifts at injection and extraction, structure resonances, the microwave instability, transverse resistive wall and head tail thresholds must all be avoided as much as possible. Multibunch instabilities will probably require damping. In this context it is useful to remember that: 1) The charge/bunch is only a factor of three beyond the Brookhaven AGS, the charge/pulse is only 50% more than is regularly achieved, and the bunch would be in the ring for only ~ 2 % of the AGS acceleration time. 2) The accelerator would be operating entirely below transition, where beams are more stable. Nevertheless, every increase in machine performance has been accompanied by the discovery of new types of instabilities.[12]

Structure resonances In general one would like to minimize the driving terms and the growth rates to give the best opportunity of extracting the beam before significant beam loss. The CERN booster has operated with very large space charge tune shifts at injection by tuning out structure resonances.

Space charge Our goal is to create a bunch hitting a target with $2.5 \cdot 10^{13}$ protons with an rms length of 1 nsec at 30 GeV, or $5 \cdot 10^{13}$ protons at 10 GeV. It seems difficult to create such a bunch in equilibrium in a ring. For example if the initial bunch at injection is space charge limited, the tune shift will be reduced by the ratio of $\beta\gamma^2$ but increased by the ratio of the bunching factor. For the case developed below, 1 GeV injection and 8 GeV extraction in a ring of length 1600 nsec, the tune shift at extraction is higher than at injection by a factor of two or three. On the other hand, large transient tune shifts have been observed.[13]

Microwave instability Short intense bunches could be expected to produce microwave instabilities, since the threshold is inversely proportional to the peak current, I_{pk},

$$\frac{Z_\parallel}{n} = \frac{F \mid \eta \mid \beta^2 E/e}{I_{pk}} \left(\frac{\Delta p}{p}\right)^2, \tag{3.2}$$

with $F = 1$. This is the "Keil-Schnell" criterion, ignoring niceties of the dispersion equation. This threshold is apparently exceeded by a factor of ten in coasting beam, and a factor of three in bunched beam in ISIS.[14] There is some disagreement about the reason for this.

Transverse Resistive Wall instability The growth times are dominated by the impedance of the kicker magnets, while the thresholds are determined by the space charge impedance. There is a relationship between space charge tune shift and transverse impedance which sets a limit to the ability to stabilize the motion with Landau damping.[15] If the space charge tune shift is at its maximum value, Landau damping will cause this limit to be exceeded. Then a fed back kicker will be needed to stabilize the lower modes

3.4 Stability of Short Bunches

The bunch hitting the target will have a peak current of 1600 A (at 30 GeV) or 3200 A (at 10 GeV) which is significantly larger than any current seen in a proton synchrotron. Although we expect instabilities, they will be moderated by three effects: 1) the large current will exist in the ring for a very short time, perhaps only a few turns, 2) the intense bunch is only required at the target, and 3) the short bunch is in many respects a more stable configuration than the long bunch that produced it.

We consider a number of instability mechanisms and their effect on an intense, one ns proton bunch. Although there are a number of options being considered, it has been necessary to look primarily at one example. We have chosen the 10 GeV option with 2.5×10^{13} protons/bunch, assuming two of these bunches could be combined at the target. In general beams are more stable at higher energies, however bunching times are also longer. Higher currents are probably more troublesome so we have not looked at the bunches with 5×10^{13} /bunch.

Structure Resonances The large incoherent space charge tune shift will require the beam to cross a number of resonance lines and will be the cause of some emittance growth, however the short bunch will last only a few turns and the growth times of these effects has been fairly long. This effect will be a more serious problem at injection.

Transverse Space Charge The incoherent space charge tune shift given by

$$\Delta\nu_{inc} = \frac{3\, r_p\, N_t}{2\, A\, B\, \beta\, \gamma^2} \approx 0.2, \tag{3.3}$$

where r_p is the classical proton radius, N_t is the number of protons per bunch, A is the phase space area of the bunch, B is the bunching factor, β and γ are the relativistic velocity and mass factors. The coherent tune shift is

$$\Delta\nu_{coh} = \frac{r_p\, N_t\, \beta_{av}\, \epsilon_1}{\pi\, \gamma\, h^2} \approx 0.0004, \tag{3.4}$$

where β_{av} refers to the average beta function around the ring, ϵ_1 is the Laslett coefficient for the vacuum chamber, and h is the vacuum chamber height. The large incoherent tune spread will tend to stabilize the beam by introducing Landau damping. The coherent tune shift is a function of the vacuum chamber shape and can be reduced by going to a circular shape where $\epsilon_1 = 0$.

Longitudinal Space Charge Space charge will cause the beam to be effected by a longitudinal voltage per turn

$$V(z) = \left(\frac{\beta^2 c^2 L}{2} - \frac{g_0\, R}{2\,\epsilon_0\,\gamma^2}\right)\lambda'(z), \tag{3.5}$$

where the first term in parenthesis is the inductive term, g_0 is a function of the beam and vacuum chamber dimensions, $\lambda'(z)$ is the derivative of the longitudinal charge density, R is the radius of the machine, ϵ_0 is the permittivity of free space, and z is the position along the bunch. This effect will tend to lengthen the beam below transition and shorten the beam above transition (negative mass instability). For the shortest bunches, the voltage produced will be equal to ~ 1 MV/turn. While very large, this voltage is much smaller then the ± 200 MeV/c momentum slewing required to bunch the proton beam, and even small compared to the momentum spread / number of turns required to bunch the beam, ± 200 MeV/50 turns $= \pm 4$ MeV/turn. In fact the perturbation on the production of a short bunch, while significant in slow bunching, is almost negligible if the bunching takes place over less than a few hundred turns. In this context it is interesting to note that the longitudinal space charge does cause an increase in the final bunch length, however the contribution to the bunch length increase is independent of the degree of bunching because as the bunch gets shorter and the voltage becomes larger, the projection onto the time axis becomes smaller, thus each turn contributes roughly the same (small) increase in bunch length. The negative mass instability can be avoided by operating below transition, as is planned. It should also be noted that the bunch shape can be controlled at injection to some extent so one can assume either a Gaussian or a parabola, which would have a linear longitudinal voltage profile.

Transverse Resistive Wall The large space charge tune spread ($\nu_{inc} \sim 0.2$) will tend to damp the beam with a time constant

$$\frac{1}{\tau_d} = \frac{\omega\,\Delta\nu_{inc}}{2\,\pi}, \tag{3.6}$$

ω being the rotational frequency of the synchrotron. With a tune spread of 0.2 this is essentially 5 turns, which is very roughly the number of turns that the short bunch would exist in the machine before extraction in the 10 GeV option. This would mean that any excitation must occur almost in a single turn, a time that is very short compared to the excitation of this effect in existing machines.

Head-Tail The bunching process involves a huge momentum slewing, and space charge induced damping. Adding chromaticity with sextupoles would produce a large tune shift between the front and rear of the bunch and would permit considerable Landau damping.

Longitudinal Microwave The Keil Schnell criterion gives the allowable range of longitudinal impedance as $Z_{\|}/n < F \mid \eta \mid \beta^2 E/e(\Delta p/p)^2/I_{pk}$, where F is a numerical factor (~ 1), η is the slip factor for dispersed beams, β is the velocity E/e is the beam energy, $(\Delta p/p)$ is the momentum spread for a given longitudinal position in the bunch, and I_{pk} is the maximum beam current. As has been pointed out by Schnell [16], bunch rotation to a shorter overall bunch length gives a more stable configuration because the momentum spread is proportional to I_{pk}, but the term in the numerator is squared, thus the allowable $Z_{\|}/n$ increases as the bunch becomes shorter. Two other points can be made: 1) The growth time of longitudinal oscillations would be roughly 1/4 of the synchrotron period for synchrotron oscillations excited by a voltage of $V = I_{pk} Z_{\|}/n$, which would be comparatively slow. 2) The CERN PS has run with beams near γ_t and found them to be stable.

High Frequency Cavity Beam Loading A rough estimate of the allowable wall impedance $Z_{\|}/n$ for high frequency loading in the rf cavities can be obtained by requiring the voltage induced to be small relative to the voltage provided by the cavities for acceleration or bunch rotation. This constraint gives the relation $(V = I_{pk}\, Z_{\|}/n) << (V_{rf} \approx 2$ MV/turn). This relation can then be used to produce limits on the high frequency behavior of the cavities.

Robinson Instability The rf cavity tuning can be adjusted to mitigate this. The cavity gap impedances may have to be actively adjusted using a high degree of local rf feedback.

Multibunch Modes Although the bunches are short, the rf frequency would be in the range of 3 - 5 MHz, so feedback and active damping should be comparatively easy to do.

Intra-Beam Scattering The intra beam scattering growth rate has been estimated and found to be quite long ($\sim$ sec) so this does not seem to be a concern for the short time the beam will be bunched.

Charge Neutralization by Residual Gas Although the bunches will be dense, normal accelerator vacuums should be able to insure that focusing by trapped electrons should be minimal, either in the accelerator or in a single purpose compressor ring.

3.5 Components

Lattice Issues The lattice has not been determined at this time. Two features may be desirable: 1) efficient use of circumference by bending magnets and RF and, 2) control of

γ_t. Since the acceleration gradients in these rapid cycling machines are on the order of 1 TeV/sec, it is desirable to have efficient use of rf, and a higher circulation frequency (smaller circumference) aids this. Control of γ_t is desirable to insure that one does not have to operate above transition, even at $\sim$ 30 GeV. It is also desirable to be able to control transition during bunch rotation.

We have considered several options for the proton driver lattice. The 30 GeV option could use a variant of the lattice proposed for the Japanese Hadron Project [3]. At 10 GeV one possible choice is a FODO lattice with eight super-periods and six cells in a super-period. The half cell length is 4.9 m and there are two long straight sections with zero dispersion per super-period and two dipoles per cell. The tunes would be $\sim$14 and γ_t would be about 12. A γ_t jump system based on a system proposed by Visnjic[17] can move the γ_t by one or more units during the bunch rotation and extraction.

We have also considered a Flexible Momentum Compaction lattice[10] for both options. This lattice can be tuned for large or imaginary γ_t, is very efficient but requires tuning for zero dispersion straight sections(see Figure 3.4). Both this lattice and that proposed for the Japanese Hadron Project seem quite sensitive to γ_t, in that quad changes of roughly 1% can move γ_t by $\sim$ 10% without significantly changing the tunes. This makes them desirable for this application.

RF System The RF system could be modeled after the cavities designed for the IPNS-II synchrotron[18]. These cavities produce 18 kV/gap over a frequency range from 1.12 to 1.50 MHz, a swing of 33%. The options considered here require higher frequencies ($\sim$ 3 MHz) but smaller frequency range (3% 30 GeV and 14% 10 GeV). A detailed design, with a larger inner radius for the ferrite rings and the smaller frequency swing, should give an acceleration gradient of greater than 15 KV/m, (see Fig 3.5). Beam loading at high intensities has been discussed by J. Griffin[19].

Injection Minimizing losses during the acceleration process will require precise control of the initial phase space distribution of the beam in both the longitudinal and transverse dimensions. The KAON Factory Study [4] described painting algorithms which will produce the desired distributions using charge exchange injection. It will also be necessary to capture any remaining neutral beam to minimize local activation.

Vacuum The large magnetic field swings required by the high repetition rate will not penetrate thick metallic vacuum chambers. The ISIS [20] synchrotron solved this problem by constructing a ceramic vacuum chamber with wires parallel to the beam on the inside of the chamber to carry the image charge. Capacitors which would pass beam frequencies and block magnet frequencies permitted the magnetic field to penetrate the wire screen. This solution works well at ISIS, but is more expensive and uses magnet apertures less efficiently than a metallic chamber.

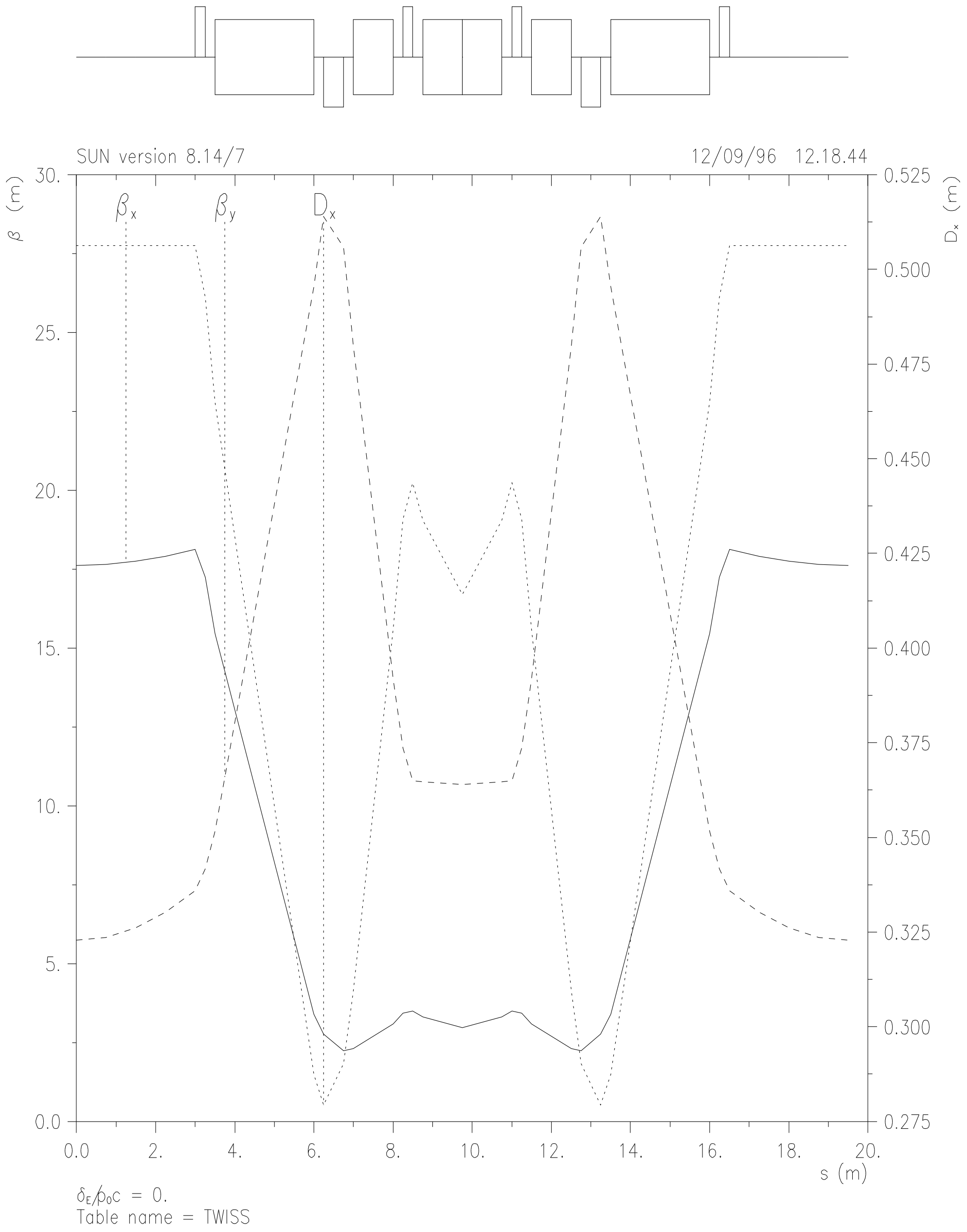

Figure 3.4: One cell of a FMC lattice.

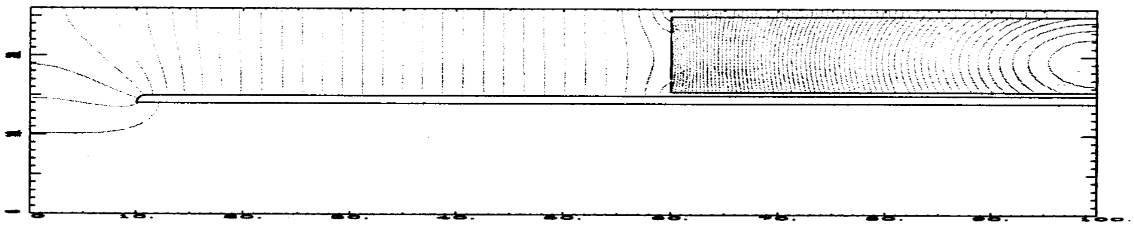

Figure 3.5: A candidate 3 - 4 MHz RF cavity. This cavity has a beam aperture of 28 cm, a length of 100 cm and would generate 15 kV/m when powered by 12 kW.

Magnets/PS Two options exist: resonant power supplies and driving the magnets directly, perhaps with some load leveling. Resonant power supplies require less load from the grid, and a two frequency system has been proposed which increases the acceleration time, while keeping the overall rate constant[21], however both systems require an uneven acceleration profile, which requires additional rf. Direct excitation of magnets would minimize the rf requirements.

Extraction The primary problem would be to avoid losses, since even a small fraction of the 5 MW of beam power would cause considerable activation of the extraction septa and downstream components. The problem has been considered for neutron spallation sources [2] [18].

3.6 Examples

It is too early to fix any parameters of the design of the proton driver. We provide some details on options which have been studied.

3.6.1 30 GeV

A proton driver operating at 30 GeV would closely follow the designs of spallation neutron sources and KAON as discussed above. The high proton energy permits transition to a short bunch using a normal bunch rotation. Compared to the 10 GeV option, the fractional momentum spread is smaller and the required charge per bunch is also smaller. On the other hand, the longer bunching time requires that the large peak current I_{pk} circulates in the synchrotron for a longer time.

3.6.2 10 GeV

A 10 GeV, 30 Hz synchrotron would operate at higher repetition rates and could be smaller, simpler and cheaper. We have considered a design with a 1 GeV linac and overall circumference of about 580 m. By eliminating one beam transfer, this system might have lower losses than a booster / driver combination accelerating to higher energy. Two bunches would be combined at the target with chicanes to give the required 5×10^{13} protons, keeping the bunches in the ring smaller. The larger momentum spread would be more difficult to confine and extract.

Because of the large fractional momentum acceptance required, we have assumed that this option would operate with the two stage bunch rotation described above. The first stage would involve running near transition and the second stage would be quick bunching with the transition energy moved moved perhaps 3 GeV above the beam energy.

Table 3.6: 10 GeV Option Parameters

	Driver	
Injection Energy	1	GeV
Max. Energy	10	GeV
Rep. Rate	30	Hz
Protons per Pulse	1×10^{14}	
Number of Bunches	4	
Circumference	580	m
Transition Gamma	11.9	
Max. Dispersion	1.6	m
Trans. Emittance [95%]	300	π mm m rad
Inc. Tune Shift Inj	.32	
RF Voltage per Turn	2	MV
Harmonic Number	6	
RF Frequency	3.3-3.7	MHz
Long. Emittance [95 %]	2.5	eVs

One possible parameter set, based loosely on designs for pulsed neutron sources, would use a FODO lattice with short bending magnets to produce a racetrack shaped ring with two long straight sections and a transition energy of about 12. An injection energy of 1 GeV would require a normalized emittance of 300 π mmmr in both x and y, and magnets with half apertures of 0.08 m.

Roughly 2 MV / turn of RF would be required. For a small number of final bunches this frequency might be in the range of 2 - 4 MHz. Assuming cavities giving 10 kV/m, these cavities might require ∼200 m of straight section space.

The 1 GeV linac for this option would be based on the FermiLab 400 MeV injector, a drift-tube plus coupled-cavity, room temperature linac. This linac presently can accelerate up to 50 mA of H^- beam at 15 Hz with a maximum 125 μsec pulse length (4×10^{13} protons per pulse or 6×10^{14} protons per sec). For a muon collider, this linac design can be upgraded to 30 Hz, 65 mA current and a 250 μsec pulse length. This would provide the needed 3×10^{15} protons per sec. The duty cycle of 7.5×10^{-3} is still comfortably low for a room temperature linac. The low energy part of this linac would consist of a 30 keV, 75 mA H^- ion source, a 2 MeV, 200 MHz RFQ and five 200 MHz DTL tanks to accelerate the beam to 116 MeV. These tanks would be nearly identical to the existing FermiLab DTL ($E_0 = 2.5$ MV/m) and could be powered by the standard 5 MW triodes.

Following the DTL would be an 800 MHz coupled-cavity linac for acceleration to 1 GeV. An average gradient $E_0 = 6$ MV/m would keep the cavity spark rate below 10^{-3} per pulse for the entire linac based on FermiLab experience. The 800 MHz linac would be 233 meters in length. This linac would be segmented into nineteen, 9 MW modules so proven Litton 12 MW klystrons could be used. Seven such klystrons power the FermiLab 400 MeV side-coupled linac. One expects the normalized emittances to be nearly the same at 400 MeV and 1 GeV. Based on present 400 MeV beam parameters, the 95% normalized transverse emittance should be 7 π mm-mrad, and the full longitudinal emittance 10^{-4} eV-sec, or 30 MeV-degrees (805 MHz), at the end of the 1 GeV linac. Scaling from 400 MeV to 1 GeV with a gradient of 6 MV/m, the full width energy and phase spreads are expected to be 3.7 MeV and 8.1 degrees. This beam will need to be debunched to reduce the energy spread for injection into the synchrotron.

3.6.3 2.5 Hz

A high energy, low rep-rate driver is also being considered. There are advantages in operating a 30 Hz driver at a 6 times lower rep-rate but with 6 times more protons / pulse. The lower rep-rate would permit much less accelerating voltage, simpler magnets, cheaper power supplies, smaller eddy current effects in metal vacuum chambers and better matching to the filling requirements of the super-conducting linacs used in the muon accelerator. The additional charge could be accommodated around the circumference of the driver without raising the peak current and the beam pulses from the Booster could be accumulated in an additional 3.6 GeV storage ring with the Driver circumference.

3.6.4 Polarized μ Production

Polarized beams can be produced from both π^+ and π^- by capturing only one polarization, although this process is inefficient. More protons are required on the target to make up for the increased losses. An additional factor of two in proton intensity at the target can be provided by adding another synchrotron in parallel. The cost of this method would be less than double the cost of a single synchrotron because many components would be used in common. The beams could be combined at the target with septum magnets in a similar manner to that proposed for combining bunches with chicanes.

3.7 R & D Issues

The proton driver described above is similar to existing synchrotrons and designs. Some R & D would be useful to evaluate bunching methods, examine instabilities that might be driven by high currents and study operating modes which minimize losses.

Bunching tests which can be done in the Brookhaven AGS can look at $I_{pk} \sim 50 - 150$ A, which approaches the range at which the acceleration would take place. This would also provide data on the nonlinearities of bunch rotation.

Both theoretical and experimental studies of instabilities in rings with high I_{pk} would be useful. Since this current would be present for a short time, during which the bunch properties would be changing rapidly, the environment would be different from that usually encountered in synchrotrons.

With a 5 MW beam it will be desirable to minimize losses to permit simple maintenance of accelerator components. There are a number of techniques which have been developed to minimize losses in high current machines, such as more efficient disposal of the linac beam in charge exchange injection, painting the phase spaces to insure minimal losses during capture and acceleration, sufficient rf to insure protons do not escape from buckets.

Bibliography

[1] G.T. Danby and J.W. Jackson, *Part. Accel.* **27** 33 (1990).

[2] 5 MW Pulsed Spallation Neutron Source, *Preconceptual Design Study* (June 1994) BNL-60678

[3] Y. Mori et al., *Outline of JHP Synchrotron Design*, Institute for Nuclear Study, University of Tokyo, Oct. 1995, INS-Rep-117.

[4] *KAON Factory Study, Accelerator Design Report*, TRIUMF, Vancouver, B. C.

[5] Cappi, Delahaye, and Reich, *IEEE Trans Nucl Sci.* **NS-28** 2389, 1981

[6] X-Q Wang, *A Study of Longitudinal Coherent Effects of Unbunched Beams Near Transition in the FermiLab Accumulator*, PhD Thesis, Ill. Inst. of Tech. (1991)

[7] J. Griffin, *Proton Driver Proposal*, unpublished note, FermiLab 1996

[8] J. Norem, *Production of Short Bunches near* γ_t, Unpublished Note, Argonne, 1996

[9] Cappi, Garoby, Mohl, Vallet and Wildner, European Particle Accelerator Conference, EPAC 94 London, June 1994

[10] Lee, Ng and Trbojevic, Phys. Rev. **E48** (1993), 3040

[11] F. Mills *Problems in the Design of a Proton Driver for a Muon Collider*, FNAL TM-1983, 1996

[12] Garayte, in Adv. of Acc Phys. and Tech., H. Schopper ed., World Scientific. Singapore 1993, p67

[13] Private communication, Alfred W. Maschke, 1972. The tune shift of several was demonstrated at injection in the AGS using the RF to bunch the beam transiently

[14] Grahame Rees, private communication, 1995.

[15] Baartman, Picacho Plaza Workshop, Santa Fe, 1993.

[16] W. Schnell, CERN Report 77-13, 1977, p231.

[17] V. Visnjic, Phys. Rev. Lett. **73** (1994), 2860

[18] IPNS Upgrade, A Feasibility Study, Argonne National Laboratory Report ANL-95/13, April 1995

[19] J. E. Griffin, *Aspects of Operation of the FermiLab Booster RF System at Very High Intensity*, Unpublished Note, FermiLab, Nov. 1995

[20] *Spallation Neutron Source: Description of Accelerator and Target*, B. Boardman ed. Rutherford Appleton Laboratory Report RL-82-006 (1982)

[21] W. F. Praeg, IEEE, Trans. Nucl. Sci. **NS-30**, (1983), 4

Contributors

- J. Norem, (ANL)
- J. Griffin, (FermiLab)
- C. Johnstone (FermiLab)
- F. Mills, (FermiLab)
- A. Moretti, (FermiLab)
- M. Popovic, (FermiLab)
- T. Roser, (BNL)

List of Figures

List of Tables