**A 10-GeV, 5-MW PROTON SOURCE
FOR A MUON - MUON COLLIDER*****RECEIVED**

FEB 08 1996

Y. Cho, Y.-C. Chae, E. Crosbie, H. Friedsam, K. Harkay, D. Horan,
R. Kustom, E. Lessner, W. McDowell, D. McGhee, H. Moe, R. Nielsen,
G. Norek, K. Peterson, Y. Qian, K. Thompson and M. White

OSTI

Argonne National Laboratory
Argonne, IL 60439

Abstract. The performance parameters of a proton source which produces the required flux of muons for a 2-TeV on 2-TeV muon collider are: a beam energy of 10 GeV, a repetition rate of 30 Hz, two bunches per pulse with 5×10^{13} protons per bunch, and an rms bunch length of 3 nsec (1). Aside from the bunch length requirement, these parameters are identical to those of a 5-MW proton source for a spallation neutron source based on a 10-GeV rapid cycling synchrotron (RCS) (2). The 10-GeV synchrotron uses a 2-GeV accelerator system as its injector, and the 2-GeV RCS is an extension of a feasibility study for a 1-MW spallation source described elsewhere (3-9). A study for the 5-MW spallation source was performed for ANL site-specific geometrical requirements. Details are presented for a site-independent proton source suitable for the muon collider utilizing the results of the 5-MW spallation source study.

1 INTRODUCTION

A feasibility study of a proton driver that generates the required number of muons for a 2-TeV on 2-TeV muon collider is presented. It utilizes the results of a site-specific study of a proton source for a 5-MW pulsed spallation source that was performed at Argonne National Laboratory (ANL) (2). The proton source performance parameters, except for bunch length requirements, are nearly identical to those of the proton driver for the muon-muon collider (1). The site-specific 5-MW proton source design was made site-independent, and was optimized as a proton driver for the muon collider.

The required performance parameters for a proton driver for a 2-TeV on 2-TeV muon collider and for a 5-MW proton source are listed in Table 1.

The 5-MW proton source is based on a 10-GeV, 30-Hz rapid cycling synchrotron (RCS-II) with a 2-GeV injector system. The 2-GeV injector is based on a system previously designed for a 1-MW spallation source that is described elsewhere in detail (3-9). The injector is comprised of a 2-GeV, 30-Hz, 190.4-meter circumference rapid cycling synchrotron (RCS-I), and a 400-MeV

* Work supported by the U. S. Department of Energy, Office of Basic Energy Sciences under the Contract W-31-109-ENG-38.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED JR

MASTER

The submitted manuscript has been authored by a contractor of the U. S. Government under contract No. W-31-109-ENG-38. Accordingly, the U. S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U. S. Government purposes.

DISCLAIMER

**Portions of this document may be illegible
in electronic image products. Images are
produced from the best available original
document.**

linear accelerator. The linac system consists of an H^- ion source, a 2-MeV RFQ, a ramped-gradient drift tube linac matching section (RGDTL), a 70-MeV DTL, a matching section, and a 330-MeV coupled cavity linac (CCL). Linac performance parameters are listed in Table 2.

TABLE 1. Comparison of Accelerator Parameters for Muon Collider Proton Driver and ANL 5-MW Proton Source

Required Performance Parameters	Muon Collider Proton Driver	ANL 5-MW Proton Source
Energy	10 GeV	10 GeV
Bunches/pulse	2	2
Protons/bunch	5×10^{13}	5×10^{13}
Bunch Length	3 nsec (rms)	~ 25 nsec (100 %)
Repetition Rate	30 Hz	30 Hz

TABLE 2. Linac Parameters

Parameters	Value	Units
Ion	H^-	
Emittance (rms normalized)	1π	mm mr
Beam Energy	400	MeV
ΔE	± 2.5	MeV
Peak Current	50	mA
Average Current	0.5	mA
Beam Power	200	kW
Removed by Chopping	25	%
Macro-Pulse Length	0.5	msec
Linac Beam Duty Factor	1.5	%
Repetition Rate	30	Hz

A key feature of the design of these accelerator systems is that beam losses are minimized from injection to extraction, reducing activation to levels consistent with hands-on maintenance. In order to minimize injection and capture losses in RCS-I, the low energy beam from the ion source is chopped at the synchrotron rf frequency, accelerated, then stacked in the waiting synchrotron buckets. At the end of the multi-turn injection, there are two gaps in the circulating beam, each corresponding to 25 % of an rf wavelength, to facilitate no-loss capture.

RCS-I accelerates 1.04×10^{14} of protons per pulse from 400 MeV to 2 GeV at a 30-Hz repetition rate. The dipole, quadrupole, and sextupole magnets for RCS-I are designed for nominal beam energies of 2 GeV but are capable of handling a maximum value of 2.2 GeV. They are powered by a dual-frequency resonant circuit that excites the magnets at a 20-Hz rate and de-excites them at a 60-Hz rate, resulting in an effective rate of 30 Hz and a reduction of 1/3 in the required peak rf voltage. The rf frequency varies from 2.2 MHz to 3 MHz during the cycle. Detailed descriptions of the RCS-I hardware can be found in Reference (3).

Two beam bunches per pulse are required at the pion production target, thus RCS-I's harmonic number was chosen to be 2. The two RCS-I bunches are separated by 332 nsec and are extracted in a single turn. The 2-GeV injector for the 5-MW proton source differs from the 1-MW spallation source RCS in harmonic number, thus a different rf cavity is required in this case. The 3-MHz RCS-I bunches are transferred into waiting buckets of the 6-MHz RCS-II rf system. The circumference ratio between the 10-GeV ring and the 2-GeV ring is four. As a consequence of this change in the rf frequency and of the ratio of circumferences of the machines, RCS-II has 16 buckets (harmonic number = 16), of which only two are occupied by the beam, separated by an empty bucket. RCS-II magnets are powered by dual-frequency resonant circuits similar to RCS-I resulting in an effective 30-Hz repetition rate. A time-averaged current of 0.5 mA, or 1.04×10^{14} protons per pulse, is achieved by this accelerator system.

The dipole, quadrupole, and sextupole magnets for RCS-II are designed for nominal beam energies of 10 GeV but are capable of handling a maximum value of 11 GeV. The gap geometries were scaled down from the corresponding magnets in the RCS-I ring to fit the smaller vacuum chambers. Calculated field qualities for the RCS-II magnets are, therefore, nearly identical to the RCS-I values. Major parameters for the synchrotron ring magnets can be found in Reference (2), along with other relevant information.

The RCS-II ring magnet vacuum chambers are 99.7% pure alumina ceramic and are similar to those used in RCS-I (3,9). There are rf shields close to the inside surface of each chamber section. A more detailed description of the RCS-II rf system, controls and diagnostics are found in Reference (2). Figure 1 shows the schematic layout of the proposed facility.

2 LATTICES

2.1 Lattice Features

Required features of the lattices for both the 2-GeV and 10-GeV rings are: 1) the transition energy must be larger than the extraction energy so that the lattice has a relatively large slip factor, $\eta = |\gamma^{-2} - \gamma_t^{-2}|$, 2) there must be enough straight-section length for the radio-frequency cavity system to provide the required energy gain using a gradient of 10 kV/m, and 3) the straight sections should be dispersion-free so that the rf cavities can be placed in dispersion-free regions. In addition, the circumference of the 10-GeV ring should be a multiple of that of the 2-GeV ring in order to have a harmonic relationship between the two synchrotron rf systems during bunch transfer from one machine to the other.

One way to satisfy requirement 1) above is for both lattices to have large horizontal tunes, since the transition energy, γ_t , is proportional to the horizontal tune. A FODO cell lattice with a phase advance of approximately 90° in both

FIGURE 1. Site-Independent 5-MW Proton Source Machine Layout

transverse planes was chosen for the normal cells of both rings in order to obtain a higher tune.

Additional advantages of 90° FODO cells are: 1) Dispersion suppression can be obtained by removing a dipole from a normal cell. 2) Normal cells without both dipoles can be used to construct the straight-section cells. 3) Focusing quadrupoles in the normal cells, the dispersion-suppressor-cells and the straight-section cells have the same strengths, and therefore only one power supply is needed for the quadrupole family. Similarly, defocusing quadrupoles in both rings can also each be powered by a single power supply.

These general design features have been incorporated in the designs of both the 2-GeV and 10-GeV lattices. Figures 2(a) and 2(b) show $1/2$ of a super period with reflective symmetry at both ends for the 2-GeV and 10-GeV lattices, respectively. Each cell of the FODO structure has a phase advance of $\sim 90^\circ$ in both transverse planes. The normal cells, dispersion-suppressor cell and the straight-section cells are evident in the figure. Dispersion suppression is achieved by removing a dipole from a normal cell. The missing dipole scheme suppresses the dispersion function when the vertical phase advance is slightly less than 90° while maintaining a horizontal phase advance of 90° . A benefit of this arrangement is that the horizontal tune is about one unit higher than the vertical tune, which is a good

(a)

(b)

FIGURE 2. Lattice Functions for 1/2 Superperiod for (a) 2-GeV and (b) 10-GeV RCS.

feature. Further study of this lattice showed that the lattice tunes can be adjusted to within $\pm 1/2$ unit while maintaining the tune difference of one unit and a vanishing dispersion function through the straight sections.

The superperiodicity of the 2-GeV ring was chosen to be four and the superperiodicity of the 10-GeV ring was chosen to be three. These numbers result from the spallation source design; however, the choice of the periodicity is arbitrary. Table 3 shows the normal cell parameters for both synchrotrons. The overall lattice parameters are shown in Table 4.

2.2 Working Point

In order to find the optimum working point, the tune region where the dynamic apertures are largest was searched while also taking into account the space charge tune shift. As a result of extensive tracking studies, the optimal tune ranges were found that provide enough dynamic aperture in both rings to contain the beam at injection (3,4,10). The lattice tunes were chosen to be $\nu_x = 6.821$ and $\nu_y = 5.731$ for RCS-I and $\nu_x = 19.20$ and $\nu_y = 18.19$ for RCS-II. The working points, including the maximum space-charge tune spread assuming an elliptic distribution, are shown in Figures 3(a) and 3(b) for RCS-I and RCS-II, respectively. The RCS-I injection mechanism is expected to result in a Kapchinskij-Vladimirskij (K-V) distribution (3). The point Q in Figure 3(a) is the working point for a K-V distribution.

The tune spread around the working point for RCS-II is clear of structure resonances. In RCS-I, the tune spread can cross two nonlinear structure resonances. The $\nu_x + 3\nu_y = 24$ resonance can be driven by skew-octupole fields, but such fields arise only from multipole errors and have little effect on the dynamic aperture. The $3\nu_x = 20$ resonance near the full space charge tune can be driven by chromaticity-correcting sextupoles and can have a deleterious effect on the circulating beam. This effect can be made small by placing harmonic-correcting sextupoles in the dispersion-free sections, a standard technique used for a synchrotron light source Chasman-Green lattice.

2.3 Dynamic Aperture

The lattices of both machines have to provide a large enough dynamic aperture to contain the beam. The dynamic aperture in each case is limited primarily by the chromaticity-correcting sextupoles. In RCS-I, although the tune spread due to $\Delta p/p$ is small, chromaticity correction may be desirable. In RCS-II, the tune spread due to $\Delta p/p$ is larger than the space-charge tune spread, thus chromaticity correction is necessary, especially during injection.

In RCS-I, with the sextupoles energized to the values required to adjust the chromaticities to zero, the dynamic aperture is larger than the beam-stay-clear (BSC), as shown in Figure 4. Detailed calculations of the effects of magnetic field

TABLE 3. Normal Cell Parameters for 2-GeV and 10-GeV RCS

2 GeV, $B_p = 9.288$ Tm			10 GeV, $B_p = 36.352$ Tm			Units
Elements	Length (m)	Strength	Elements	Length (m)	Strength	
QD	0.25	-6.765	QD	0.4	-13.086	T/m
D1	0.3		DQS	0.2		
SD	0.2	-39.15	SD	0.4	-118.05	T/m ²
D1	0.3		DSB	0.675		
B	1.3	1.403	B	1.727	1.377	T
D2	0.8		DBQ	1.275		
QF	0.5	7.685	QF	0.8	13.536	T/m
D1	0.3		DQS	0.2		
SF	0.2	28.42	SF	0.4	78.52	T/m ²
D1	0.3		DSB	0.675		
B	1.3	1.403	B	1.727	1.377	T
D2	0.8		DBQ	1.275		
QD	0.25	-6.765	QD	0.4	-13.086	T/m

TABLE 4. Lattice Parameters for 2-GeV and 10-GeV RCS

Parameters	2-GeV RCS	10-GeV RCS	Units
Circumference	190.4	761.6	m
Superperiodicity	4	3	-
Total number of cells	28	75	-
Number of normal cells	12	45	-
Number of dispersion-suppressor cells	8	6	-
Number of straight-section cells	8	24	-
Normal cell length	6.8	10.155	m
Bending radius	6.621	26.392	m
Number of dipole magnets	32	96	-
Dipole magnets effective length	1.30	1.727	m
Dipole field strength at extraction	1.40	1.377	m
Dipole field strength at injection	0.48	0.352	m
Number of quadrupole magnets	56	150	-
Quadrupole magnet effective length	0.5	0.8	m
Maximum quadrupole gradient (B')	7.73	13.54	T/m
Number of sextupole magnets (F)	16	42	-
Number of sextupole magnets (D)	16	48	-
Sextupole magnet effective length	0.2	0.4	m
Sextupole field coefficient (B'')	40	118.1	T/m ²
Transition energy, γ_t	5.4	14.74	-
Horizontal tune, ν_x	6.821	19.20	-
Vertical tune, ν_y	5.731	18.19	-
Natural chromaticity, $\xi_x = (\Delta\nu)_x/(\Delta p/p)$	-7.23	-23.90	-
Natural chromaticity, $\xi_y = (\Delta\nu)_y/(\Delta p/p)$	-6.88	-23.06	-
Maximum β_x	12	16.84	m
Minimum β_y	11	17.26	m
Maximum dispersion function	2.2	1.0	m

FIGURE 3. Integer and Half-Integer Stop-Bands and Structure Resonances Through Fourth Order Including Working Point (P) and Tune Spread for (a) RCS-I and (b) RCS-II. In (a), the maximum space charge tune shift for a uniform, K-V distribution is labeled Q.

imperfections, misalignments, and orbit corrections are reported in References (3,4).

The lattice dynamic apertures at the design tune and at the depressed tune for the RCS-II are shown in Figure 5. The beam size at injection and the BSC are also shown. In Figure 5(a), we show the dynamic apertures at the chromaticities $\xi_{x,y} = 0$ and -5 . The operating range of the chromaticity is expected to be close to $\xi_{x,y} = -5$, where the dynamic aperture is shown to be larger than the BSC. In Figure 5(b), we show the dynamic aperture when the working point is moved to the space-charge depressed tune.

FIGURE 4. Dynamic Aperture of the RCS-I Lattice at the Design Tune. Details of the calculations are found in References (3,4).

3 APERTURES AND ACCEPTANCES

The stacked beam transverse emittance (100%) in RCS-I is 375π mm mr. The beam is damped to 128π mm mr at 2 GeV when it is injected into RCS-II. The BSC acceptance for both machines is defined as being twice the emittance and the $\pm 1\%$ momentum spread of the incoming beam. Figure 6 shows the vacuum chamber cross-sections of RCS-I (a) and RCS-II (b) at a focusing quadrupole indicating the BSC and the injected beam envelope.

4 INJECTION AND BEAM TRANSFER

For injection into RCS-I, multiple turns are accumulated using charge exchange by stripping the H^- linac beam. This, together with programming the closed orbit during injection, allows transverse phase space painting to achieve a K-V-like distribution of the injected particles in RCS-I (3,5,6). The 400-MeV injection energy, a stacked emittance of 375π mm mr in both transverse planes, and an allowed space charge tune shift of about 0.17 results in a space charge limit of 1.04×10^{14} protons.

For injection into RCS-II, bunch-to-bucket transfer is used. Each pulse of the 2-GeV extracted beam contains two bunches. The beam from RCS-I has a single bunch area of 3.7 eV sec; this bunch is transferred into a slightly larger waiting bucket in RCS-II. Matching between the bunch and the bucket is performed using the following algorithm. The rf voltage at the extraction of the 2-GeV beam determines the energy spread, ΔE , and length, Δt , of the bunch. The energy spread

FIGURE 5. Dynamic Aperture of the RCS-II Lattice at Different Chromaticities. (a) Lattice at the Design Tune. (b) Working Point at the Space-Charge Depressed Tune $\nu_x = 19.08$ and $\nu_y = 18.07$, where a Uniform Charge Distribution is Assumed.

FIGURE 6. Focusing Quadrupole Vacuum Chamber Cross Section in (a) RCS-I and (b) RCS-II Showing Beam-Stay-Clear (dashed line) and Beam Envelopes (area containing diagonal lines). Note that the scale is different in the two drawings.

and bunch length of the incoming beam are matched to a Hamiltonian phase space contour of the waiting bucket. The space charge distortion of the contours is taken into account in these calculations to prevent mismatching and consequent dilution of the beam. Figure 7(a) shows the rf bucket and the bunch population in RCS-I at extraction, when the rf voltage is 200 kV. Figure 7(b) shows the bunch injected into the waiting bucket of RCS-II. The required rf voltage at this time is 700 kV. The dashed line in Figure 7(b) represents the Hamiltonian contour whose height, ΔE , and whose enclosed area are equal to those of the injected beam. This shows that the 3.7 eV sec bunch is matched to a contour of a 3.7 eV sec phase space area within a 5.8 eV sec bucket.

FIGURE 7. (a) Rf Bucket and Phase Space Distribution at Extraction in RCS-I. The Bunch Area is 3.7 eV sec. (b) Rf Bucket and Phase Space Distribution at Injection in RCS-II. The Dotted Line Indicates the Contour Enclosing an Area of 3.7 eV sec.

5 RF VOLTAGE PROGRAM

The key feature of the design studies for both the 1- and 5-MW machines was to determine the rf voltage program that results in no beam loss from injection to extraction. Such a program was obtained for each machine using a Monte Carlo method to track the particles from injection to extraction (11). The rf voltage programs for the accelerating cycles of both rings are depicted in Figures 8(a) and 8(b). The time variation of the bucket and bunch areas are also shown in the figures. The rf voltage program allows the capture and acceleration of 1.04×10^{14} particles per pulse with minimum loss of particles during the beam transfer and acceleration processes.

5.1 Rf Voltage at Injection

RCS-I accepts the 400-MeV beam from the linac and accelerates it to 2-GeV. Capture with minimum losses is obtained by chopping the linac beam such that it occupies 75 % of the ring. A beam with ± 2.5 MeV energy spread is injected in

FIGURE 8. Rf Voltage Programs for (a) RCS-I and (b) RCS-II, Showing Time Evolution of the Bucket (solid line) and Bunch (dotted line) Areas Over the Complete Cycle.

561 turns, which corresponds to 0.5 msec. The area of the chopped incoming beam is 1.7 eV sec per bunch. A minimum rf voltage of 81 kV is required to contain the beam during the initial injection. The corresponding per-bucket area is 3.5 eV sec. During injection, the rf voltage must be increased from 81 kV to 134 kV to prevent beam losses. This rapid increase in the voltage is crucial to overcome the space charge forces that increase with particle density as multiple turns are accumulated. At the end of injection, the per-bucket area is 4.5 eV sec, and the single bunch area grows from 1.7 eV sec to 3.7 eV sec, giving a dilution factor of 2.2.

The unloaded bunch-to-bucket matching into RCS-II is straightforward, as discussed in the previous section. However, transient beam loading is expected to be severe, and either a low-impedance cathode-follower or a feed-forward system needs to be investigated.

5.2 Rf Voltage During Acceleration

The rf voltage in RCS-I is raised during the first 6 msec of acceleration to maintain a fixed per-bucket area of 4.5 eV sec and reaches a maximum of 220 kV at this time. The voltage is gradually decreased to 200 kV from 6 msec to the end of acceleration. The per-bucket area grows to 21 eV sec at extraction. The voltage for the latter part of the cycle is maintained high to ensure a synchrotron frequency fast enough to allow the particles in the bunch to follow the rapid change of the synchronous phase near extraction. The Keil-Schnell criterion for longitudinal stability is also met by making the bucket area large. The per-bunch area is 3.7 eV sec throughout the cycle.

In RCS-II, the initial per-bucket area is 5.8 eV sec, as described in the previous section. The per-bucket area is maintained at this initial value for the first 8 msec, and the voltage reaches 1.9 MV at this time. The voltage is decreased to 1.7 MV over the remainder of the cycle, giving a per-bucket area of 106 eV sec at extraction. The voltage for the latter part of the cycle is maintained high for the same reason as in RCS-I. The bunch height is ± 102.5 MeV and the full bunch length is 22.6 nsec at extraction from RCS-II. The per-bunch area is 3.7 eV sec. The final bunch length can be shortened by rf manipulations, as explained in detail in the following section.

6 BUNCH LENGTH ADJUSTMENT

The required bunch length at the pion production target is 3 nsec rms, or 15 nsec full length (1). The typical full bunch length at extraction from RCS-II is about 25 nsec. The bunch length can be compressed through rf manipulations just prior to extraction. One way to shorten a bunch is to suddenly increase the rf voltage for a quarter synchrotron period. The initial bunch has $\pm \Delta E_i$ and $\pm \Delta \phi_i$ prior to the sudden voltage jump. The sudden jump of the rf voltage causes the bunch to rotate with a synchrotron frequency derived from the final voltage, V_f . After a quarter synchrotron period, the initial bunch has rotated 90° in phase space so that ΔE_i is projected onto to the ϕ -axis. The following relation is obtained for a stationary bucket when the bunch area is much smaller than the bucket area:

$$\sin^2(\Delta \phi_f / 2) = \frac{\pi h |\eta|}{2 \beta^2 e E_s} \frac{(\Delta E_i)^2}{V_f}.$$

In this equation, $\Delta \phi_f$ is the half-length of the final bunch, E_s is the total energy of the synchronous particle, β is the relative velocity, and e is the unit electric charge. The above equation shows that the final bunch length is related to the increased voltage and the initial energy spread. The initial energy spread is determined by the voltage before the sudden increase.

Figure 9 shows the results of tracking studies of this bunch length adjustment process. Figure 9(a) shows the rf voltage program throughout the acceleration cycle. The voltage step from $V_i = 1.2$ MV to $V_f = 3.2$ MV is shown near the end of the cycle. The voltage is increased in 50 μ sec, and the higher voltage is maintained for 0.45 msec. Figure 9(b) shows the particle phase space distribution just prior to the voltage increase. The full bunch length is 25 nsec and the bunch has a $\Delta p/p$ of 0.9%. Figure 9(c) shows the phase space distribution after a quarter synchrotron period (0.45 msec) after the voltage increase to V_f . The new full bunch length is 15 nsec, which corresponds to 3 nsec rms, and the new $\Delta p/p$ is 1.5%. This bunch is contained within a BSC momentum acceptance of 4.4% at extraction. The space charge tune shift at extraction for the shortened bunch is about 0.1.

FIGURE 9. Bunch Length Adjustment at Extraction from RCS-II: (a) is the RCS-II Rf Voltage Program Including the Voltage Step, (b) is the Particle Distribution in Phase Space Just Prior to the Voltage Increase and (c) is the Distribution at Extraction.

7 IMPEDANCE AND INSTABILITIES

Longitudinal and transverse instability thresholds were obtained from the estimated coupling impedances. The transverse impedance is dominated by the space charge self-field. The contribution to the longitudinal impedance from space charge dominates in RCS-I. In RCS-II, the space charge impedance is comparable to that from the broadband rf cavity impedance. Beam parameters such as $\Delta p/p$ and peak current were obtained through Monte Carlo studies of beam capture and acceleration using a longitudinal tracking code that includes the effects of space charge (11). The analyses lead to rf voltage profiles and beam parameters that minimized the instabilities as well as beam losses (3,7,8).

Both RCS-I and RCS-II operate below the transition energy, thus the longitudinal microwave instability is not expected to occur unless there is a large resistive component. However, a conservative approach was adopted to ensure that the momentum spread is sufficient to satisfy the Keil-Schnell (KS) stability criterion. In RCS-I, the ceramic vacuum chamber is constructed with a special rf shield, such as that used at the ISIS facility of Rutherford-Appleton Laboratory (12), to minimize the impedance due to space charge. The shield follows the beam envelope at an aperture equal to the BSC, reducing both the longitudinal and transverse space charge impedances by between 30 and 35 % at injection. In RCS-II, the space charge impedance is smaller than in RCS-I by a factor of 5 at injection and 10 at extraction. Therefore, a contour-following rf shield, such as that used in the RCS-I, is not required. The rf shields are close to the inside surface of each chamber section. Studies were performed to choose an rf voltage profile that provides adequate bucket area and momentum spread. Tracking studies show that the RCS-I beam remains in the stable region defined by the KS criterion over the duration of the acceleration cycle (3,7). The KS criterion is more difficult to satisfy in RCS-II because the threshold is dominated by the high peak current. Tracking studies show that the RCS-II beam remains in the stable region through most of the acceleration, where, at extraction energy, the $\Delta p/p$ is about 1% and the bunching factor (peak/circulating current) is about 0.01. The peak current in RCS-II is 160 A at injection and less than 800 A at extraction.

In the transverse plane, the head-tail instability was analyzed in both machines. The growth rate is proportional to the resistive wall and kicker impedances. The head-tail modes are stabilized at a slightly negative chromaticity. The threshold tune spread for transverse microwave instability is 0.06 in RCS-I and 0.11 in RCS-II.

8 SUMMARY

A feasibility study of a proton source that generates the required number of muons in a 2-TeV on 2-TeV muon collider is presented. The results of a 5-MW, 10-GeV proton source study for a pulsed spallation neutron source were used.

The accelerator configuration for the muon collider proton source consists of a 400-MeV H^- linac, a 2-GeV RCS-I and a 10-GeV RCS-II, each operating at 30 Hz and an average current of 0.5 mA. RCS-I accepts the 400-MeV H^- beam and accelerates it to 2 GeV in an $h = 2$ rf system. The linac beam is chopped at the source at the injection rf frequency so that when multi-turn injection is completed, there are two gaps in the circulating beam, each corresponding to 25% of an rf wavelength. This gap is introduced to facilitate no-loss capture. For both RCS's, low losses are achieved by providing large dynamic apertures in the transverse planes and sufficient bucket areas in the longitudinal space. The extracted pulse for the pion production target consists of two bunches with 5×10^{13} protons each and whose length can be made about 3 nsec rms by the introduction of a sudden jump in the rf voltage. The corresponding $\Delta p/p$ is 1.5%.

9 REFERENCES

1. R. B. Palmer, et. al., "Beam Dynamics Problems in a Muon Collider," BNL Report 61580 (March 16, 1995) and references therein.
2. Y. Cho, et. al., "A 10-GeV, 5-MW Proton Source for a Pulsed Spallation Source," *Proc. of 13th Meeting of the Int'l. Collaboration on Advanced Neutron Sources*, PSI, Villigen, to be published (Oct. 11-14, 1995).
3. "IPNS Upgrade - A Feasibility Study", ANL Report ANL-95/13 (April, 1995).
4. E. Lessner, Y.-C. Chae, and S. Kim, "Effects of Imperfections on Dynamic Aperture and Orbit Functions of the IPNS Upgrade Synchrotron," *Proc. of the 1995 Particle Accelerator Conference*, Dallas, Texas, to be published (May 1995).
5. Y.-C. Chae and Y. Cho, "Study of Field Ionization in Charge Exchange Injection for the IPNS Upgrade," *Proc. of the 1995 Particle Accelerator Conference*, Dallas, Texas, to be published (May 1995).
6. E. Crosbie and K. Symon, "Injecting a Kapchinskij-Vladimirskij Distribution into a Proton Synchrotron," *Proc. of the 1995 Particle Accelerator Conference*, Dallas, Texas, May 1995, to be published (May 1995).
7. K. Harkay, Y. Cho, and E. Lessner, "Longitudinal Instability Analysis for the IPNS Upgrade," *Proc. of the 1995 Particle Accelerator Conference*, Dallas, Texas, to be published (May 1995).
8. K. Harkay and Y. Cho, "Transverse Instabilities Analysis for the IPNS Upgrade," *Proc. of the 1995 Particle Accelerator Conference*, Dallas, Texas, to be published (May 1995).
9. Y. Cho, et al., "Feasibility Study of a 1-MW Pulsed Spallation Source," *Proc. of 13th Meeting of the Int'l. Collaboration on Advanced Neutron Sources*, PSI, Villigen, to be published (Oct. 11-14, 1995).
10. Y.-C. Chae and Y. Cho, "Study of the High γ_t Lattice for a 5-MW Proton Synchrotron: FODO-I," ANL Report No. NSA-95-6 (August 11, 1995).
11. Y. Cho, E. Lessner, and K. Symon, "Injection and Capture Simulations for a High Intensity Proton Synchrotron," *Proc. of the European Particle Accelerator Conference*, London, page 1228 (1994).
12. G. H. Rees, "Status Report on ISIS," *Proc. of the IEEE Particle Accelerator Conference* (March 16-19, 1987).

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.