Beam Dynamics Studies for Proposed Proton Therapy Facility

D. Raparia and W. Funk
Superconducting Super Collider Laboratory*
2550 Beckleymeade Ave., Dallas, Texas 75237

Abstract

A proton therapy facility is proposed at the Superconducting Super Collider (SSC). The facility will use proton beam from SSC Linac. The SSC Linac can provide the discrete intermediate energies of 70, 110, 157, 210, 268, and 329 MeV by drifting the beam in the high-energy end of the Linac, which is not exited with rf power. 250 MeV is expected to be the maximum energy needed for therapy. This paper summarizes beam dynamics studies for different energies.

I. Introduction

The linear accelerator (LINAC) [1] is the first injector in the chain of four injectors for the Superconducting Super Collider (SSC). The SSC Linac will provide up to 600 MeV beams. The main beam parameters out of the SSC Linac are listed in Table 1. The availability of H^- beams of suitable energy and current at the end of Linac offers an attractive opportunity for a medical facility for proton therapy. At the request of Southwestern Medical Center, Particle Accelerator Corporation (PAC) in collaboration with Lawrence Berkeley Laboratory (LBL) and Aguirre Association Inc. has done tradeoff studies of several options, all of which would parasitically use the H^- beams accelerated by the SSC Linac [2], [3]. They have recommended to treat patients with the Linac beam directly after passing through a series of devices to reduce its intensity appropriately. This approach provides a treatment time of less than two minutes and a dose controllability of a factor of ten below the desired dose uniformity. The dose control requires a system time response of only 0.1 second, which is easily achievable.

II. Beam Formation and Transport systems

As shown in Table 1, the Linac operates in the so called 'collider fill' mode and 'test beam' mode. The most demanding mode from injector point of view is 'test beam' mode. The scenario for 'test beam' mode to use the Linac beam for medical use is as follows. The LEB cycle time is 0.1 seconds and each LEB 'batch' is injected into the Medium Energy Booster (MEB). The MEB takes six batches from the LEB and accelerates the total injected beam to full energy (199100 MeV) in a period of 8.7 seconds. During this MEB acceleration process, the Linac and LEB are in a standby mode and available for medical use. If the MEB accelerated beam is used to inject into the High Energy Booster (HEB), which has a cycle time of 516 seconds, the availability of the linac beam for the medical application is grater. Thus in the test beam mode, the Linac as available for 8.2 seconds out of every 8.7 seconds, give or take a possible pulse on each end of the 8.2 sec that might be used in ramping quadrupole magnets for their medical values. The therapy beam can be interleaved with LEB injection pulses. The pulse availability in time is shown schematically in fig 1.

Collider Fill Mode	
Current	21 mA
Pulse length	9.6 μsec
Proton per Macropulse	1.26 x 10^{12}
Trans. Emittance (n,rms)	$\leq$0.3 πmm mrad
Rep. Rate	10 Hz
Test Beam Mode	
Current	21 mA
Pulse length	48 μsec
Proton per Macropulse	6.30 x 10^{12}
Trans. Emittance (n,rms)	$\leq$0.3 π mm mrad
Rep. Rate	10 Hz

Table 1: The SSC Linac Beam Parameters

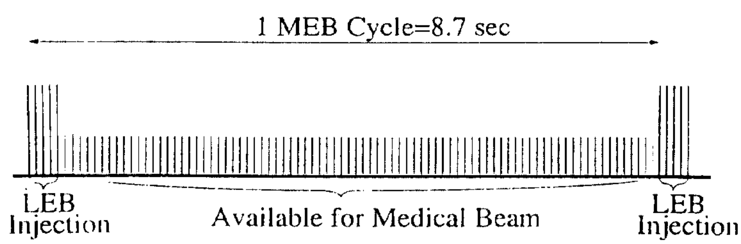

Figure 1: Linac Pulse Structure

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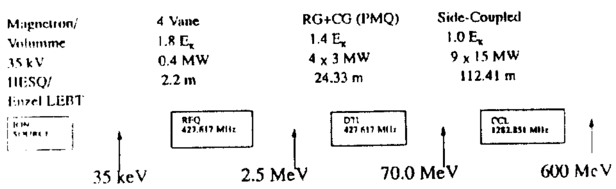

Figure 2: SSC Linac Block Diagram

A schematic layout for the SSC Linac is shown is figure 2. The Drift Tube Linac (DTL) will accelerate the beam up to 70 MeV. The Coupled (side) Cavity Linac will take this beam and accelerate up to 600 MeV. The CCL has 9 modules powered by 9 Kystrons. By delaying the rf power into the CCL modules, the energies available for medical use are shown in Table 2. CCLDYN [4] simulations have shown that it is possible to drift a lower energy beam through higher-energy modules in the CCL, which are not exited with rf power during the passage of the beam. The beam cavity interaction for an unexcited module is not important because beam has a time structure of 428 MHz and the CCL cavity resonance frequency is 1283, the third harmonic of the beam. Moreover the field in the cavity which is excited by the beam will have the a random phase with respect to the beam, therefore on the average the beam will not be affected when it passes though the RF unexcited cavities. However, it is necessary to lower the excitation of quadrupoles for the lower energy beam if the beam is to remain well-enough focused to pass through the small beam apertures of the modules without loss. The quarupole gradients for the discrete intermediate energies are shown in Table 2. Figure 3 shows the 70 MeV beam profiles for energy spread, phase spread and beam size, through the CCL. The quadrupole gradient required is down to 10.0 T/m whereas for normal operation quadrupole strength is 31 T/m. Figure 4 shows energy spread, phase spread and beam size for 250 MeV through the CCL. The quadrupole gradient needed for this is 31 T/m for modules 1 through 4 and 20 T/m for modules 5 through 9.

The quadrupole magnets are made of laminated steel so that they can be rapidly pulsed (0.1 sec) to lower values to accommodate lower-energy beams. The maximum energy needed for therapy is 250 MeV.

The beam for therapy will be diverted to the proton therapy facility in the Linac-LEB transfer line between the Q1, Q2 doublet and the Q3, Q4 doublet with help of a three magnet bump. The schematic layout of these magnets is

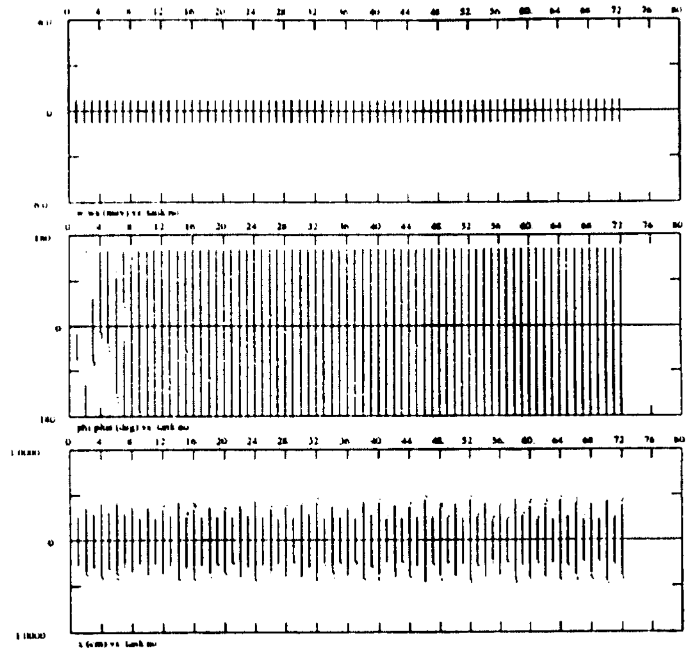

Figure 3: 70 MeV Beam size, phase and energy profiles as beam traverses the CCL

Table 2: Available beam energy for proton therapy.

Energy MeV	RF Excited		RF Unexcited	
	Module No	G (T/m)	Module No	G (T/m)
70	-	-	1-9	10.0
110	1	31.0	2-9	12.0
157	1-2	31.0	3-9	14.4
210	1-3	31.0	4-9	16.8
267	1-4	31.0	5-9	19.2

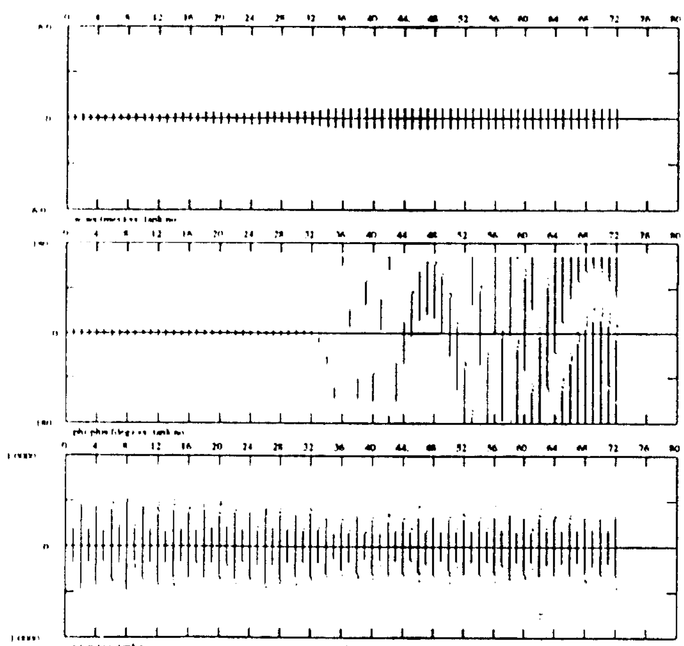

Figure 4: 250 MeV Beam size, phase and energy profiles as beam traverses the CCL

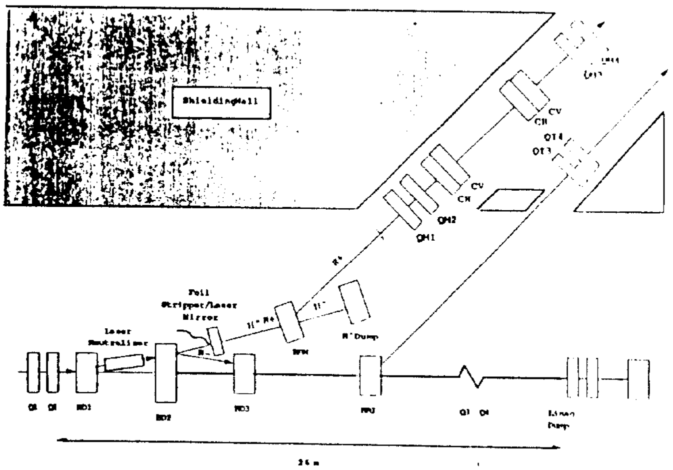

Figure 5: Schematic Layout of Bump Magnets

shown in figure 4.

The bump magnet BD1 bends the H^- beam 5.59 deg away from the Linac axis to provide enough transverse space for the second bump magnet BD2 and longitudinal space for a device to neutralize a small portion of beam. A cw laser LS installed as shown before the second bump magnet is sufficient to neutralize a small fraction of the H^- beam. It is also fail-safe. The second bump magnet bends the H^- beam back toward the Linac axis (thus BD2 has twice the bend angle of other bump magnet) while the H^0 beam passes through the magnet undeflected. Third bump magnet BD3 bends the H^- back onto the Linac axis. A stripping foil is placed in the H^0 beam beyond the second bump magnet to provide an H^+ beam.

III. CONCLUSIONS

The SSC linac can provide the required energy and more than adequate intensity for the proton therapy. The only change which has been made in the Linac design to accomodate the proton therapy beam is the laminated quadrupole magnet.

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IV. REFERENCES

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