Design and Simulation of a 50 MeV Superconducting Proton Linac

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Abstract

We present the preliminary design of a three-stage lattice consisting of a radiofrequency quadrupole section (RFQ), a medium-energy beam transport section (MEBT), and a superconducting (SC) linear accelerating section (SCL). Focusing is performed with SC solenoids. Two types of SC cavities are used in two different sections of the SCL; one section contains one cavity and one solenoid, and the other section contains two cavities and one solenoid. Simulations with TRACE 3-D code show a stable beam envelope, avoidance of emittance growth, and proper matching of beam and lattice parameters.

1 Introduction

Linear accelerators (linacs) have a long history in experimental and applied physics. Radiofrequency variation of the fields allowed linacs to become viable as particle acceleration devices that could avoid electrical breakdown fields. Recently, SC technology has allowed linacs to reach extremely high power-transfer efficiency, through the use of liquid helium cooling. Such SC linacs have proven to be extremely useful in exploring the structure of the nucleus, with e^- linacs aiding our understanding of quarks and nucleon substructure. Additionally, linacs have made major contributions in other areas of science, most notably medicine. The application of linacs as X-ray sources in hospitals is one of the great triumphs of applied physics.

Some of the major aspects of RFQ+MEBT+SCL design include focal length of the magnetic quadrupole, focal length of the SC solenoids, accelerating gradient of the SC cavities, and power dissipation of the structure. As such, we will utilize several results concerning these values from the theory of accelerator physics. Recall that the focal length of a magnetic quadrupole is given by

$$\frac{1}{f_Q} = \pm \frac{qGl}{mc\gamma\beta} \tag{1}$$

where q is the charge, G is the quadrupole gradient, l is the length, m is the particle mass, c is the speed of light, and β and γ are the usual relativistic factors. The $\pm$ represents a focusing or defocusing quadrupole, respectively. Other focusing structures obey the same form. The solenoid focal length is given by

$$\frac{1}{f_S} = \left(\frac{qB}{2\gamma m\beta c}\right)^2 l \tag{2}$$

where B is the magnetic field of the solenoid. The RF cavity focal length is given by

$$\frac{1}{f_G} = \frac{\pi q E_0 T L sin(-\phi)}{mc^2\lambda(\beta\gamma)^3} \tag{3}$$

With the focal lengths given, we can concern ourselves now with the actual acceleration of the protons. The energy gain in an RF SC cavity is given by

$$\Delta W = qE_0 T L cos(\phi_s) \tag{4}$$

where ΔW is the energy gain, E_0T is the accelerating gradient, L is the length, and phi_s is the synchronous phase of the cavity. The transit time factor T in the accelerating gradient has an additional factor from a synchronous phase-dependent piece, as seen in the complete form given by

$$T = \frac{sin(\pi g/\beta\lambda)}{\pi g/\beta\lambda} sin(\pi\beta_s/2\beta) \tag{5}$$

The $sin(\pi\beta_s/2\beta)$ factor, where β_s is the synchronous beta given by $\beta_s\lambda = g$, is a major issue in maximizing the energy gain of a proton as it passes through an SC cavity. The final preliminary design parameter we will be concerned with is the total power dissipation of the beam is given by

$$P_B = \frac{I\Delta W}{q} \tag{6}$$

Now we are ready to discuss the specifics of the 50 MeV linac. Beginning with design parameters, we will progress to the actual design and refining procedure utilizing TRACE 3-D, and finally present our findings in the results and conclusions sections.

2 Design Parameters

The RFQ will have a frequency of 162.5 MHz, and will obey the peak field relation $E_{peak} \approx 1.6E_K$, where E_K is the usual Kilpatrick field magnitude. The MEBT will have a length of about 3 meters, and room temperature quadrupole combinations (doublets, triplets) are allowed. The longitudinal emittance upon entry will be 400π keV deg. The SCL will have 2-gap cavities operating in π-mode, with length $\beta_G\lambda$, where β_G is the geometric beta. The focusing SC solenoids will have a field $B_{sol} \leq 8T$, and the maximum accelerating gradient E_0T will be 8 MV/m, and this value only includes the non-β_s-dependent portion of T. A standard choice of $\phi_s = -\frac{\pi}{6}$ will be made. The maximum current for intended operation is chosen to be 50 mA.

3 Design

The design process is split into three sections - RFQ, MEBT, and SCL. After parallel development, the lattice components will be matched with a procedure described below.

3.1 RFQ

The purpose of the RFQ is to bunch the beam and provide initial acceleration from 60 keV to 5 MeV. TRACE-3D severely limits any attempt at detailed RFQ design, so we design the last two RFQ cells and disable any acceleration. Therefore, the beam will enter this last section of the RFQ as a 5 MeV beam. Modulation will be set at $m = 2$. For RFQ stability, we require a phase advance per cell of between 40 and 90 degrees. From the design parameters and stability requirement, we can express every needed simulation parameter of the RFQs as a function of the vane radius a. The only design task left is therefore a matching of phase advance to the MEBT via a choice of vane radius a.

3.2 MEBT

The task of the MEBT is to connect the beam from the RFQ to the SCL and provide Twiss parameter matching to prevent emittance dilution. We attempted to obey the following constraints in the transport line design:

- The transfer line operates at room temperature and provides focusing using conventional quadrupoles.
- To match the Twiss parameters in the transverse plane, we need at least 4 quadrupole magnets.
- To match the Twiss parameters in the longitudinal plane, we need at least 2 RF gaps.
- Quadrupole strengths should be less than 100 T/m.
- Transverse beam size should be reasonable, less than 5 cm.

Additionally, we obey the 3 meter total length requirement stated in Design Parameters.

3.3 SCL

Two types of cavities were designed - Type A cavities have a fundamental frequency of $f_A = 162.5$ MHz, and type B cavities have $f_B = 325$ MHz. Thus, B cavities are simply a second harmonic of A cavities. Type A will accelerate protons from the initial velocity of about $0.1c$ to about $0.2c$, and type B will carry them the rest of the way to $0.3c$, which is approximately 50 MeV. As such, we choose a geometric beta for type A of $\beta_{GA} = 0.15$ and a geometric beta for type B of $\beta_{GB} = 0.25$. The lengths of the cavities can now be calculated to be $L_A = 22.1$ cm and $L_B = 23.0$ cm. The total energy gain per cavity given by Eq. 4 can now be used to find out exactly how many cavities are necessary for the SCL. We utilize 15 type A cavities and 21 type B cavities. The solenoid field strengths are determined via an attempted matching to the focal length of the RF cavities, but the adiabatic increase of field strength is favored over this criteria in general. That is to say, the field will be increased gradually until the criteria is approximately satisfied. The increase in accelerating gradient is also adiabatic, and constrained so that we only experience a maximum of 10% increase in kinetic energy per cavity. The stability of the beam is assumed to be fairly strong by the time type B cavities are introduced, so we choose an accelerator periodicity as follows. Type A cavities will have a 1-to-1 ratio of cavities-to-solenoids, and type B will have a 2-to-1 ratio.

3.4 Final Matching

When we speak about final matching of the beam to the accelerator lattice, we are referring to the equivalence of the well-known Twiss parameters of the beam and upcoming lattice throughout the entire structure. This means that the beam out of the RFQ must be matched to the beginning of the MEBT lattice, and the beam out of the MEBT must be matched to the Twiss parameters of the initial SCL lattice.

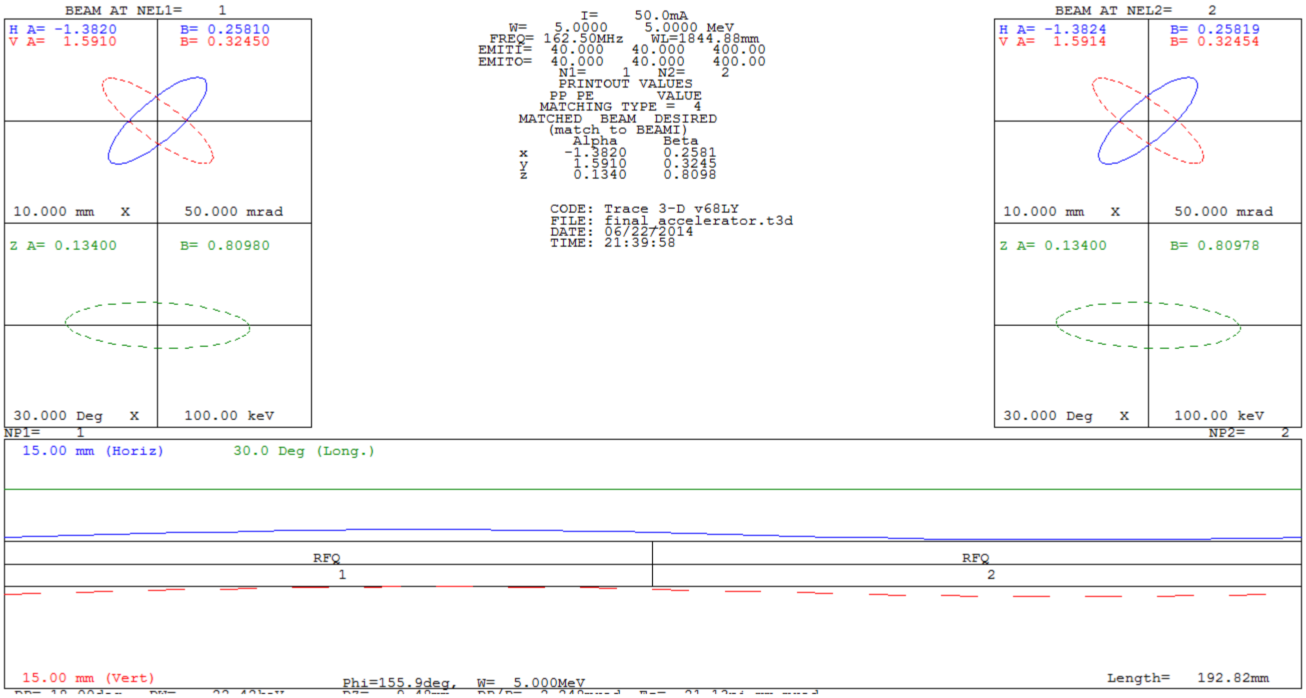
The Twiss parameter matching for the RFQ yields a phase advance of 44.03 degrees, which implies a vane radius of 5.5 mm. All other TRACE 3-D parameters can now be calculated as $\frac{XV}{a^2} = 1.85$ mm, $AV_0 = 77.76$ kV, $L = 96.41$ mm, $\phi = \frac{-\pi}{6}$. The second RFQ will be set at $-\pi$ for optimal TRACE 3-D operation.

The final MEBT design contains four 15 cm quadrupoles, grouped into a singlet and triplet, operating at approximately 0.1 T/m. It also contains two RF cavities with $\phi_s = \frac{\pi}{2}$, providing approximately 0.5 MV of potential. The total length is 1.34 m.

The SCL portion should enjoy an almost perfect matching from the RFQ and MEBT, and we expect a well-contained beam envelope and healthy beam parameters.

4 Results

With the above design, we analyzed the machine in TRACE 3-D at the design current of 50 mA. Figs. 1 and 2 show the RFQ and MEBT sections alone, respectively.



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     W=   5.0000     5.0000 MeV
   FREQ= 162.50MHz   WL=1844.88mm
  EMITI=  40.000    40.000    400.00
  EMITO=  40.000    40.000    400.00
          N1=     1   N2=     2
          PRINTOUT VALUES
         PP PE        VALUE
        MATCHING TYPE =  4
      MATCHED  BEAM  DESIRED
         (match to BEAMI)
            Alpha       Beta
      x    -1.3820     0.2581
      y     1.5910     0.3245
      z     0.1340     0.8098

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         DATE: 06/22/2014
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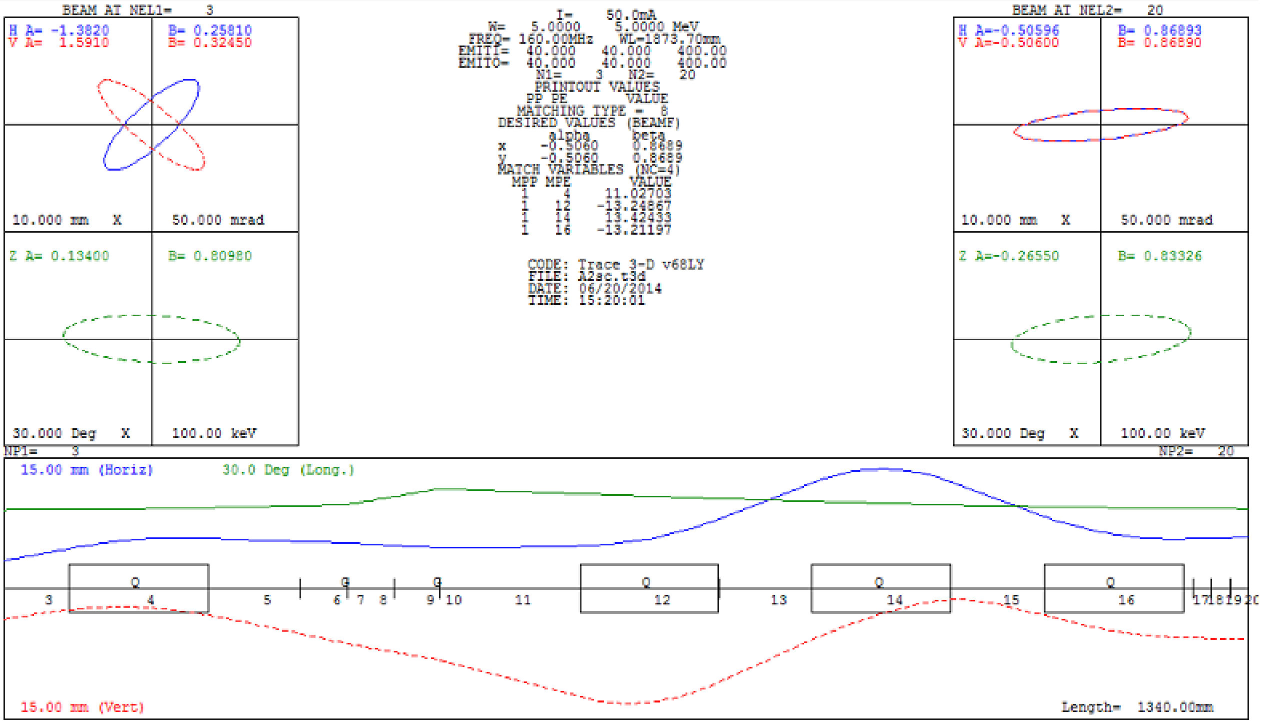
Figure 1. RFQ section of lattice.

We note that rotating coordinates must be used for the SCL section (with a trailing ”1” in the TRACE 3-D solenoid element description) in order to properly calculate the axially symmetric beam progression.



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     W=   5.0000     5.0000 MeV
   FREQ= 160.00MHz   WL=1873.70mm
  EMITI=  40.000    40.000    400.00
  EMITO=  40.000    40.000    400.00
          N1=     3    N2=    20
          PRINTOUT VALUES
         PP PE        VALUE
        MATCHING TYPE =  8
      DESIRED VALUES (BEAMF)
            alpha      beta
      x    -0.5060    0.8689
      y    -0.5060    0.8689
      MATCH VARIABLES  (NC=4)
        MPP MPE        VALUE
          1   4     11.02703
          1  12    -13.24867
          1  14     13.42433
          1  16    -13.21197

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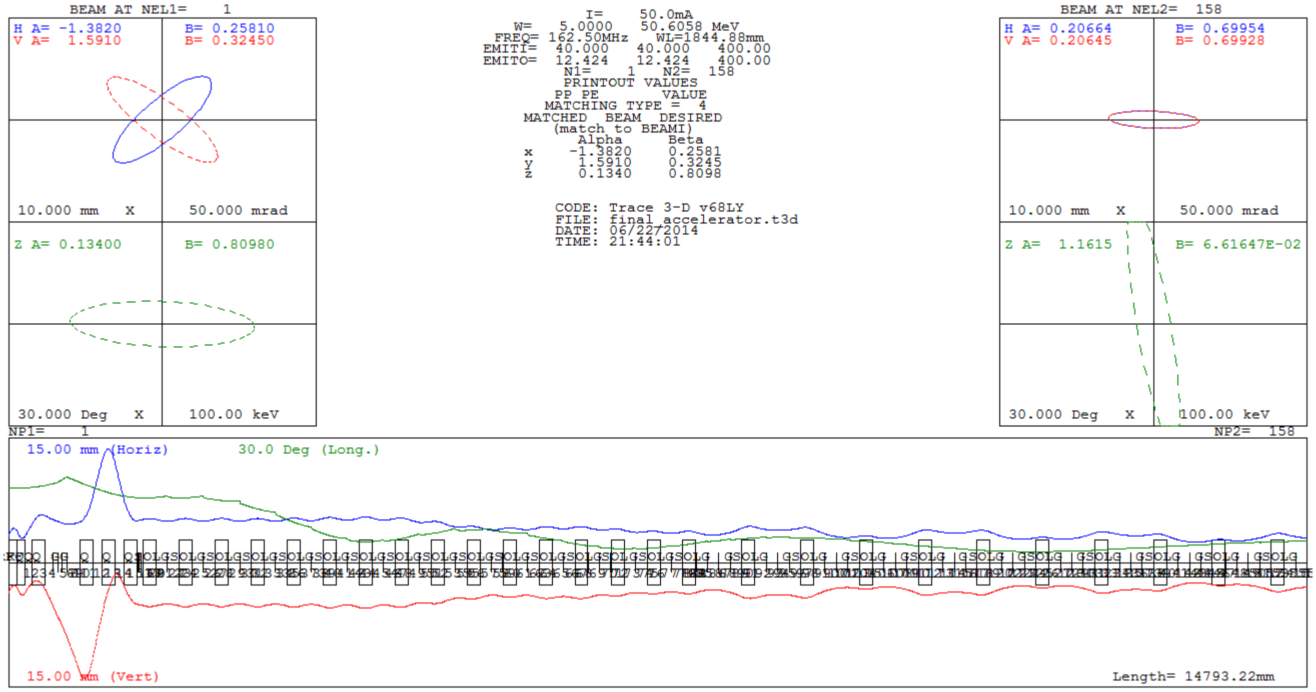
         DATE: 06/20/2014
         TIME: 15:20:01
```

Figure 2. MEBT section of lattice.

The final design energy of 50 MeV is slightly exceeded in the SCL portion, but this can always be tweaked via lower accelerating gradients without much effect on beam stability, as long as the changes are kept adiabatic.



```
           I=     50.0mA
   W=   5.0000    50.6058 MeV
 FREQ= 162.50MHz   WL=1844.88mm
EMITI=  40.000    40.000    400.00
EMITO=  12.424    12.424    400.00
          N1=     1   N2=  158
          PRINTOUT VALUES
         PP PE        VALUE
        MATCHING TYPE =  4
      MATCHED  BEAM  DESIRED
         (match to BEAMI)
            Alpha      Beta
      x    -1.3820    0.2581
      y     1.5910    0.3245
      z     0.1340    0.8098


         CODE: Trace 3-D v68LY
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         TIME: 21:44:01
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Figure 3. Simulation of RFQ+MEBT+SCL lattice.

As can be seen in Fig. 3, which displays the entire lattice simulated in TRACE 3-D , the final matching is very accurate, providing a smooth progression and minimal envelope oscillations. Note that the transition between periodicity, which occurs approximately halfway through the lattice, is almost indiscernible. This suggests a well-matched and stable optics. For ramping stability analysis, we plotted the energy gain per cavity versus cavity number (Fig. 4).

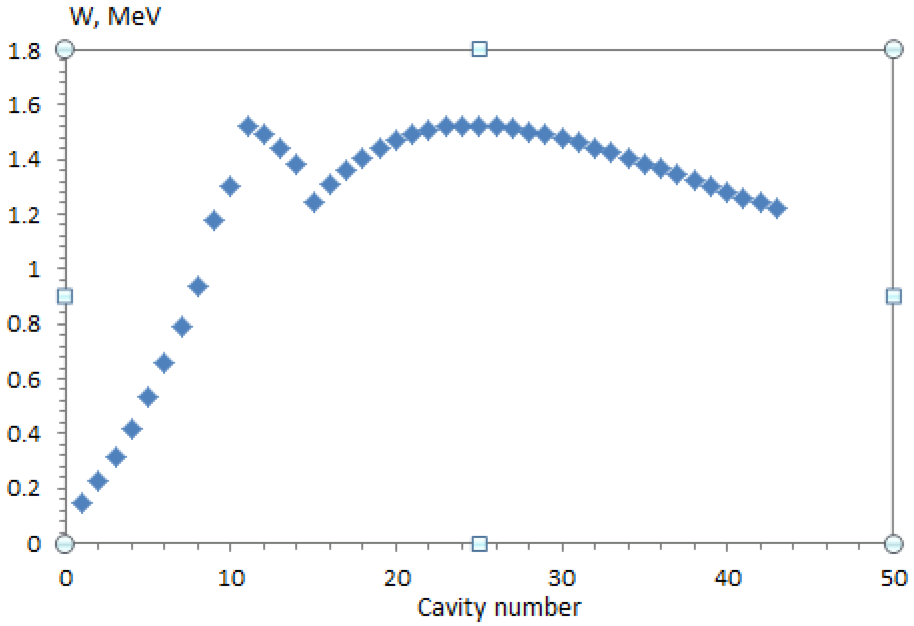

Figure 4. Energy gain per cavity versus cavity number. Note the adiabatic ramping of accelerating gradient.

Fig. 4 clearly shows smooth ramping balanced with efficient gradient use. With the stability of the beam and lattice confirmed, we finally calculate the necessary beam power using Eq. 6 to be $P_B = 2.25$ MW, which can easily be supplied with three 1 MW klystrons. The total accelerator length is less than 15 m.

5 Conclusions

We have designed and simulated, using TRACE 3-D, a 50 MeV superconducting proton linac for operation at 50 mA. We use two types of cavities in the SCL, matched by a singlet and triplet plus two RF cavity MEBT, which receives the beam from the RFQ section. The beam and lattice are matched to a reasonable degree. Analysis with TRACE 3-D suggests that the lattice is completely stable for the given input beam emittance and design parameters. The power and length are within the expected order of magnitude.

6 References

1. Wangler, T. P. *RF Linear Accelerators*. 2 ed. WILEY-VCH, 2008.