Transition Section Between a 200 MHz Drift Tube Linac and a High Gradient Coupled Cavity Linac for the Fermilab Upgrade

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Introduction

The upgrade of the Fermilab 200 MeV H^- linac is a project proposed as an element of a program to enhance the performance of the Tevatron Collider. By replacing the last four of nine 200 MHz drift tube accelerating tanks with high gradient 805 MHz structure the exit energy is raised from 200 to 400 MeV within the existing linac enclosure.[1] The performance of the booster synchrotron will be improved because of the reduced spacecharge tuneshift, reduced importance of remanent fields, smaller transverse emittance of the injected beam, increased available rf bucket area, and reduced scattering of the circulating protons by the H^- stripping foil during injection. A reference design reflecting the current development of the conceptual design is described in a companion paper.[2]

After the main objectives of the Linac Upgrade program were determined about two and one half years ago, one of the first pressing problems to be addressed was the 3-D matching of the linac beam from the low gradient, low frequency Alvarez structure with quadrupoles in drift tubes to the high gradient, high frequency structure with quadrupoles in bridge couplers. In particular it was necessary to change structure at such an energy that there would be sufficient space in the existing building to operate the high frequency structure at an acceptable gradient. It soon became apparent that a few meters were sufficient to match the transverse coordinates. In the longitudinal coordinate, several methods were investigated. First, an adiabatic transition section was studied in which the matching parameter (gradient) was changed in high frequency structure according to the usual adiabatic law . It was found that in order to reduce dilution due to bunch shape oscillations, it was necessary to make the section a quarter wave long in phase oscillations. This made the section much too long, since it started at a very low gradient in order to match to the lower frequency. Further, the technical problem of constructing cavities with the proper adiabatic law appeared extremely challenging. Second, a rotation section was investigated in which the uniform gradient was chosen to rotate the beam ellipse by 90° from the match at low frequency to that at high frequency. This resulted in a low gradient high frequency section about 4 m long, which was acceptable since it seemed to fit the needs of the transverse coordinates and did not consume appreciable power. It was shown that with the present linac emittance, this method would work up to a frequency of 1.2 GHz before nonlinearities would cause appreciable dilution. The natural choice for this option is 805 MHz because the rotator is then similar to the accelerating structure. A third option, several isolated cavities, was considered briefly, but was rejected since it offered no improvement in performance, and required much more in the way of phase and amplitude control. This report develops the concept of the bunch rotator and transverse matching section with reference to the properties of the beam from the 200 MHz linac at 116.5 MeV, the end of tank 5.

116 MeV Beam Properties

Emittance measurements can be made in the present linac in the transport from the ion source, at the end of 10 MeV tank 1, and at 200 MeV. One can use the particle dynamics code PARMILA to derive from these widely separated measurements a prediction for the six-dimensional beam phasespace distribution at 116 MeV. The reliability of the prediction is severely limited by inadequate knowledge of the alignment errors and the dependence of quad gradients on current. Furthermore, empirical tuning over the years has resulted in an irregular pattern of quad settings which invalidates inferences from design parameters. The PARMILA predictions[3] and other parameters defining the requirements for the transition section are collected in Table 1. The Twiss parameters are improbable for beam emerging from an alternating gradient focusing lattice; both transverse beam envelopes are near a divergence minimum. Whether or not this result expresses the real situation, it serves as a caution that the transverse matching must be flexible enough to adapt to conditions far from the nominal. The linac can of course be retuned to provide better initial match. The final two quads in the linac are included as elements of the transverse matching section; the PARMILA tank 5 exit prediction is arbitrarily applied one drift tube upstream.

Kinetic energy	116.54	MeV
Beam current, averaged over pulse	50.	mA
Longitudinal emittance ε_L (90 %)	6.2	$\times 10^{5}\pi$ eVs
Transverse emittance $\varepsilon_{x,y}$ in (90 %)	10.	π mm mrad
Estimated Twiss parameters		
β_x	2.49	m
α_x	0.00	
β_y	5.25	m
α_y	-0.41	
β_φ @ 200 MHz	0.017	deg/keV
α_φ @ 200 MHz	0.075	deg/keV/m
Drift tube linac		
frequency	201.25	MHz
effective gradient E_0T (exit)	1.82	MV/m
accelerating phase φ_s	-32.	deg
FODO half-cell (exit)	67.9	m
exit aperture	2.0	cm
Coupled cavity linac		
frequency	805.0	MHz
effective gradient E_0T (entrance)	7.16	MV/m
accelerating phase φ_s	-32.	deg
FODO half-cell (entrance)	163.8	cm
entrance aperture	1.5	cm
Matched waist		
β_x	1.73	m
β_y	8.35	m
β_φ @ 805 MHz	0.014	deg/keV

Table 1: 116 MeV Beam Parameters and Matching Requirements

Longitudinal Matching

Matching is achieved by rotating the longitudinal phasespace ellipse 90° without acceleration by rf voltage chosen so that the upright ellipse has the ratio of major to minor axis matched to the accelerating gradient. The canonical variables corresponding to the invariant longitudinal emittance in eVs are the difference ϵ of the particle energy

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from the synchronous value and the difference τ between the time the particle reaches the center of the accelerating gaps and the time when the rf is at the synchronous phase φ_s. Because $\Delta s/s = \Delta\beta/\beta$, $\tau = \Delta s/\beta c = (s/\beta c)\Delta\beta/\beta$. Thus,

$$\frac{d\tau}{ds} = \frac{1}{\beta c}\frac{\Delta\beta}{\beta} = \frac{1}{\beta c(\beta\gamma)^2}\frac{\Delta\gamma}{\gamma} = \frac{\epsilon}{c(\beta\gamma)^3 m_o c^2} = a\epsilon \ .$$

The energy difference is given by

$$\frac{d\epsilon}{ds} = eE_0T(\cos\varphi - \cos\varphi_s) \approx -eE_0T\sin\varphi_s\omega\tau = -b\tau \ ,$$

where $E_0T\cos\varphi_s$ is the average effective acceleration gradient and ω is the angular frequency of the rf. These linearized equations of motion are derivable from a Hamiltonian

$$H = a\frac{\epsilon^2}{2} + b\frac{\tau^2}{2} \ ,$$

which is a constant of the motion. The curve of the equation $H = H_o$ is an ellipse with semi-axes $\sqrt{2H_o/a}$ and $\sqrt{2H_o/b}$. By equating energy semi-axis to $\sqrt{\varepsilon_L/\beta_m}$ and time semi-axis to $\sqrt{\varepsilon_L\beta_m}$, where β_m is the β matched to the rotating potential, one finds directly $\beta_m = a/b$.

The initial condition for the rotation is $\epsilon_i = \sqrt{\varepsilon_L/\beta_i}$ so that $H_o = a\varepsilon_L/2\beta_i$. After 90° of rotation the bunch width must be matched to $\tau_f = \sqrt{\varepsilon_L\beta_f}$ so that $H_o = b\varepsilon_L\beta_f/2$. Consequently,

$$\beta_i\beta_f = a/b = \beta_m^2 = (cm_oc^2(\beta\gamma)^3\omega eE_0T\sin\varphi_s)^{-1} \ .$$

The result that the correct β for the quarter oscillation matching is the geometric mean of the β's in the initial and final gradients looks like impedance matching. By combining the first order equations of motion one finds

$$\frac{d^2}{dt^2}\tau + ab\,\tau = 0 \ ,$$

so that the length of the rotator is one fourth of the wavelength of the phase oscillation, *viz.*,

$$(ab)^{\ 1/2}/4 = \sqrt{cm_oc^2(\beta\gamma)^3/(\omega eE_0T\sin\varphi_s)}/4 \ .$$

Using the parameters from Table 1, one finds that 1.8 m of rotator with average axial gradient of 0.95 MeV/m is required starting from an uncorrelated initial beam. However, the PARMILA prediction is not matched to the nominal tank 5 parameters. There is a unique gradient and length for each matching condition. The necessary degrees of freedom to match a range of conditions without changing length are obtained by dividing the rotator structure into two independently powered parts which can be run at different gradients. Dividing the rotator in half provides a place where transverse matching quad(s) can be located. The effect of the debunching in the gradient free-region is to reduce the required gradient and increase the required length of rotator. Numerical calculation is used to establish the number of cells for a reasonable range.

Transverse Matching

The 116 MeV beam exits an alternate gradient focusing channel with final quad spacing of 68 cm; the spacing in the new linac starts at 159 cm. The disparity in focusing cell lengths means that the matching section will contain irregular beam envelopes. A minimum of four variable focusing elements are needed to provide for matching the four ellipse parameters. Conservatively, at least one additional degree of freedom is indicated to ensure that solutions exist for a safe range of initial conditions and to reduce the probability of solutions with extreme widths in the matching section. Two formulations of the problem which lead to different physical layouts are introduced. The relative merit of the two schemes has not yet been evaluated. Considerations of flexibility, ease of adjustment, and ease of fabrication will be answered in ongoing design study.

The last two quads of the drift tube linac will be treated as part of the matching section. They can either be treated as a widely spaced doublet or a short half FODO cell. The advantage of the first choice is that a transition section consisting of doublets at beginning, middle, and end provides sufficient degrees of freedom without further division of the rotator; it therefore saves valuable space. The second alternative generally leads to less irregular beam envelopes because it continues a roughly FODO pattern. However, to get matching elements into the structure, two more divisions of the rotator are required which add to the length both by the length of the bridge couplers introduced and also by additional debunching effect. In either case the length of the intermediate cells does not fall naturally between the lengths of preceding and succeeding cells. Therefore, the 1.5 cm radius beam aperture adopted for the accelerating structures may not be adequate for some possible initial conditions. Because this structure runs at low gradient there is little need to restrict the cavity beam aperture for high shunt impedance. Both rf structure and quadrupoles should have wider aperture in the matching section than in the new linac.

	Element	Length [cm]	Bore rad. [cm]	Gradient [kG/m]	E_0T [MV/m]
1	quad	16.5	2.2	82.1	
2	drift*	51.4			
3	quad	16.5	2.2	-88.3	
4	drift	34.5			
5	rf tank	255.3			0.799
6	drift	5.0			
7	quad	8.0	2.0	255.0	
8	drift	16.5			
9	quad	8.0	2.0	-168.1	
10	drift	5.0			
11	rf tank	255.3			0.229
12	drift	5.0			
13	quad	8.0	2.0	55.2	
14	drift	4.3			
15	quad	4.0	2.0	-205.2	
		693.3			

* rf gap treated as drift

Table 2: Doublet Transition Section Parameters

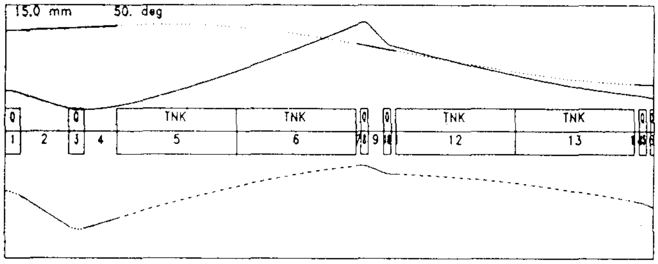

Figure 1: Beam envelopes and layout for the doublet based transition section

Transition Section Parameters and Layout

The layout of the doublet version of the transition section appears in the beam envelope plot, Fig. 1, produced by TRACE-3D[4] which is used for all of the beam optics. The parameter values for the initial conditions of Table 1 appear in Table 2. The final quad is part of the down stream focusing lattice and therefore is constrained, but small changes that result only in moving the waist longitudinally by a few mm are permissable.

The FODO version of the transition section appears in Fig. 2. The parameters values are given in Table 3.

	Element	Length [cm]	Bore rad. [cm]	Gradient [kG/m]	E_0T [MV/m]
1	quad	16.5	2.2	86.4	
2	drift*	51.4			
3	quad	16.5	2.2	-100.2	
4	drift	34.5			
5	rf tank	127.7			0.775
6	drift	8.8			
7	quad	8.0	2.0	182.4	
8	drift	8.8			
9	rf tank	127.7			0.775
10	drift	8.8			
11	quad	8.0	2.0	-181.4	
12	drift	8.8			
13	rf tank	127.7			0.325
14	drift	8.8			
15	quad	8.0	2.0	157.6	
16	drift	8.8			
17	rf tank	127.7			0.325
18	drift	17.3			
19	quad	4.0	2.0	-205.2	
		727.8			

* rf gap treated as drift

Table 3: FODO Transition Section Parameters

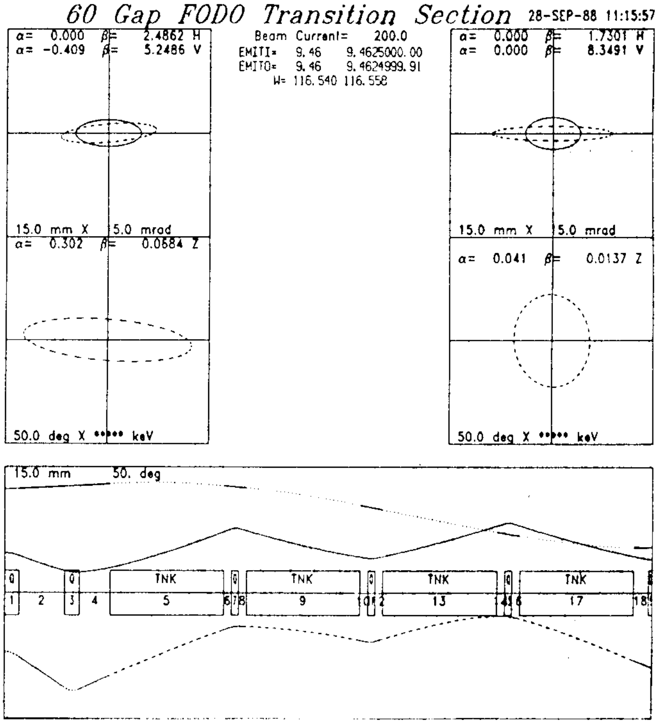

Figure 2: Beam envelopes and layout for FODO transition section

Summary

The transition at 116 MeV between tank 5 of Fermilab's 200 MeV H^- linac and a proposed 400 MeV 805 MHz side coupled linac requires both longitudinal and transverse phase plane beam matching. The design of the transition section is based on a 90° longitudinal phase oscillation at intermediate gradient combined with a sufficient number of quadrupoles to match transverse beam ellipses and simultaneously limit extreme beam width in the matching process. Both doublet and FODO variants of the transverse matching are satisfactory in concept; the choice is part of current design work.

References

[1] *Antiproton-Proton Collider Upgrade: Linac Conceptual Design*, Fermi National Accelerator Laboratory (February 1988)

[2] J. A. Maclachlan, "Reference Design for the Fermilab Linac Upgrade", preceding paper

[3] Elliott McCrory, priv. comm.

[4] K. R. Crandall, "Trace 3-D Documentation", Los Alamos report LA 11054-MS(August 1987)