400 MeV Upgrade for the Fermilab Linac

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Introduction

Fermilab has plans for a comprehensive accelerator upgrade to open new possibilities for both the fixed target and collider experimental programs.[1] An early step in this program is to increase the energy of the linac from 200 to 400 MeV by replacing the last four of its nine 201 MHz Alvarez tanks with twenty-eight 805 MHz side-coupled cavity chains operating at about 8 MV/m average axial field. The principal purpose is to reduce the incoherent spacecharge tuneshift at injection into the Booster which currently limits both the brightness of the beam, an important determinant of collider luminosity, and total intensity to produce both the antiprotons for the collider and the beams to fixed target experimental areas. Other consequences of higher Booster injection energy expected to contribute to some degree to higher intensity limits and improved operational characteristics include improved quality of the guide field at injection, reduced frequency swing for the rf systems, and smaller emittance for the injected beam. The linac upgrade project[2] has moved from a 1986 study through a development project including structure models[3],[4] and numerical studies[5] to a full-feature module prototyping starting this year.

General Design Criteria

The present 201 MHz drift tube linac (DTL) consists of nine accelerating tanks; the last four span 66 m and accelerate the H^- beam from 116.5 to 200 MeV. Even when the linac was designed over 20 years ago more efficient and more compact accelerating structures were known for energies above 100 MeV, but it was convenient and expeditious to stick with a single structure type throughout. The fundamental assumption in the upgrade design is that the 400 MeV replacement for the last four tanks should fit within the same length so that the change-over can be quick and simple. Therefore, the new structure (SCL) must support over three times the existing gradient. From a literature survey[6] it was determined that it would be reliable to operate a short-pulse ($\sim 100\mu s$) linac with maximum surface field up to $1.6E_K$, where E_K is the conventional Kilpatrick limit on the surface field to avoid sparking in a cw system with vacuum maintained by oil diffusion pumps:[7]

$$f = 1.643 E_K^2 e^{-8.5/E_K} \quad ,$$

where f is the frequency in MHz. For cavities optimized for maximum shunt impedance, the maximum surface field E_{max} is about five times the average axial field E_o. Because E_o must be about 8 MV/m, the new linac should operate with at least four times the frequency of the old. Higher gradient is easier at higher frequency, but the emittance of the 201 MHz bunches plus consideration of non-linearity in the bunch length matching using a buncher at the high frequency place a limit somewhere below 1.5 GHz. Because it seemed that development of an appropriate klystron would be required and the cost of that klystron would not depend strongly on frequency within the useable range, the frequency was fixed at 805 MHz to leave some margin for error in the matching and rf timing.

The properties of the beam at 116 MeV, determined from nominal parameters and a mix of calculation and measurements at other energies, and the provisional constraints taken to define the design problem are given together in Table 1. In general it has not appeared necessary or advantageous to modify the initial constraints. The radius of the beam passage between the accelerating gaps is a sensitive parameter affecting the transit time factor T and effective shunt impedance ZT^2; an initial choice $r_b = 1.5$ cm, less than the 2 cm exit bore of the DTL, was made to start the cavity optimization. It has not proved possible to relax significantly this somewhat tight aperture and meet other design goals. To make the 400 MeV upgrade a self-contained project, the quoted 116 MeV emittances are taken as fixed conditions. Improvements which may be anticipated in these quantities as the result of other work would be welcome for relaxing requirements on beam steering *etc.*, but are not required to satisfy the project goals.

Reference Design

The reference design for the new linac is a self-consistent set of those parameters meeting the design goals of the upgrade which are necessary to define a common basis for work in progress. It represents the current stage of evolution from conceptual design to engineering design, now approaching the stage where a realistic prototype module can be built.

Starting from the cavity geometry of the LAMPF linac as further optimized by Lloyd Young of Los Alamos at 200 MeV, the transit time factor T, the effective shunt impedance ZT^2, and the maximum surface field E_{max} normalized to average axial field $E_o = 1$ MV/m have been calculated[8] using SUPERFISH as functions of Lorentz $\beta = v_p/c$ for cavity parameters re-optimized at eight different energies between 116 and 400 MeV. The calculated value of ZT^2 has been reduced by 12 % to account for the slots providing 5% coupling between adjacent accelerating cavities. It has been reduced a further 3 % to allow for surface defects, and fabrication artifacts like brazed joints. These values are fitted by least squares to a cubic polynomial in powers of β to provide simple functional representations.

From these fits one calculates the number of cavities and the gradients which gives the desired acceleration in the available space. The cavities are grouped into chains sufficiently short that the beam can be kept in the aperture by focusing elements located between the chains. The energy gain is then recalculated with all cavities in a given chain having length $\bar{\beta}\lambda/2$ where λ is the free-space wavelength of the rf and $\bar{\beta}$ is the so-called geometrical β, very nearly the same as the β for the mean energy in the chain. The chains are combined into modules which are excited by separate klystron transmitters. Quadrupoles are placed between chains; chains within a module are joined by a side-coupled bridge cell of length $3\bar{\beta}\lambda/2$ ("bridge coupler") which carries the rf around the quads while maintaining synchronism between the rf and the beam. The bridge coupler at the center of a module has an iris to receive the rf drive. The bridge coupler is chosen to be a single-cell, post-stabilized TM010 cavity patterned after the shorter of the LAMPF bridge couplers;[10] the length of the Fermilab couplers does not require a more elaborate design. Small adjustments in gradients and number of cells per chain are made to equalize the power/module with a common gradient for all chains in a given module in order to arrive at a final final set of parameters. The process described is a multi-dimensional optimization which can converge at least to a local optimum quickly and unambiguously for a satisfactory choice of initial constraints. The art of the design of course lies in that choice. Table 2 summarizes the parameters of the SCL linac modules.

*Operated by the Universities Research Association under contract with the U. S. Department of Energy

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Transverse Focusing

The accelerating structure must be divided into short enough chains that the focusing elements are spaced to keep the beam envelope satisfactorily within the aperture. The transverse kick from a $\beta\lambda/2$ cavity is

$$\frac{\Delta r'}{r} = \frac{\pi/2\, e\mathrm{E}_0 T \sin\varphi_s}{m_0 c^2\, \beta^2\gamma^3} .$$

Beam spacecharge is a small effect for the SCL; it has the same dependence on β and γ as the rf defocusing. By numerical calculation[9] or, neglecting spacecharge, by the formula just given one can calculate the minimum of the maximum transverse beam envelope as a function of the length of the cavity chain. Because the aperture and the beam emittance are given design constraints, the result is the maximum acceptable length of the chain resulting from the focusing scheme. Because the rf input to the modules is at the center, there must be an even number of chains per module. A scheme where there are just two long chains with symmetric quadrupole triplets located between modules is not viable because the zero-current transverse phase advance per focusing period exceeds 90° thereby giving rise to a transverse instability.[11] With four chains/module the number of cells that can be powered by the 12 MW klystron[1] result in chains short enough for a FODO focusing scheme. The FODO pattern has been adopted. The equalization of the power dissipation among modules resulted in a choice to make all modules contain the same number of cavities. Therefore, the length of both chains and bridge couplers increase directly as β. By using the same spacing $3\beta\lambda/2$ between modules as used between chains within a module, a regular focusing lattice is obtained. Although this results in tight fit between earlier modules for all that is desired in the inter-module space, it has additional advantage in conserving space and minimizing debunching. Not much extension of the inter-module spacing is required to introduce a significant asymmetry between the two transverse phase planes because the inter-module spaces are all occupied by the same sign of focusing element. The minimum of the maximum beam envelope is also increased by lengthening the inter-module spaces. When the completely regular focusing arrangement is used, the quad strength that provides the minimax beam envelope in the first focusing cell works for the other cells as well. Thus, quads of 8 cm magnetic length and 23 T/m gradient are used between all cavity chains. The resulting beam properties are indicated in Table 2. The beam envelopes are shown in Fig. 1.

The quads being designed for this application are electromagnetic quads with 3 cm poletip radius to allow room within for a beam position monitor. Adopting $3\beta\lambda/2$ spacing between modules results in only 28.5 cm between modules one and two. To aid in fitting the desired vacuum valve, beam toroid, beam position monitor, and beam steering into the limited space, the quadrupole will be built in a clamshell structure that can be put around the beampipe after it has been installed, and the steering will be implemented with auxiliary windings on the quad. Therefore, despite the fact that all quads have the same strength, permanent magnet quadrupoles are not favored.

Transition Section

The DTL provides stronger transverse focusing and weaker longitudinal focusing than the following SCL. The matching requirements are summarized in Table 3. To shorten the bunches a 805 MHz buncher consisting of a five-cavity chain is placed immediately after the DTL. There is an appropriate buncher voltage and downstream drift for the particular α_z and β_z of the 201 MHz bunches; as long as the bunch width is reasonably within the linear range of 805 MHz phase, the value of the longitudinal emittance is not a consideration. However, the ellipse parameters are not known with certainty and may be subject to operational variability. Therefore, a three-cavity chain is located about a third of the way along the drift to provide correction for a range of initial conditions.

For transverse matching a minimum of four matching quads should be provided to match ellipse parameters in each plane. To increase the range of initial conditions which can be matched and to control the maximum beam envelope in the matching section, at least one more quad is indicated. To match as smoothly as practicable from the DTL focusing to that for the SCL, the matching quadrupoles should be spaced by successively greater separations, smoothly interpolating between the last DTL spacing and the first in the SCL. The drift needed for the bunching does not accommodate six spaces meeting this prescription. However, it works out reasonably to use the last three quads of the DTL as part of the transverse matching section. These plus two quads in the buncher drift give four steps of change in quad spacing. This arrangement requires lengthening the buncher drift by ~ 10%, but with the second buncher cavity available such a small change in the length is easily within the tuning range.

The calculated[9] beam envelopes in the matching section are shown in Fig. 2. Because the transverse phase advance is greater in the SCL focusing cells, the beam aspect ratio is larger. The need for this beam shaping means that the transverse envelopes in the matching section are not so regular as might be expected from the reasonably regular quad spacing. Nonetheless, the general character of a FODO focusing channel is maintained.

[1] Fermilab has a development contract with Litton Industries

Acknowledgements

Fermilab has had strong collaboration from Los Alamos, James Stovall and Lloyd Young in particular, in the design and fabrication of a side-coupled cavity and bridge coupler prototype. The design described reflects contributions from the entire Fermilab linac upgrade working group.

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Initial kinetic energy (T_i)	116.54	MeV
Final kinetic energy (T_f)	400.	MeV
Length, including transition section	<64	m
Frequency of rf (f)	805.0	MHz
Beam current averaged over pulse ($\bar{I}_b$)	50.	mA
Beam pulse length	< 100.	μs
Repetition rate	15.0	Hz
Accelerating phase (φ_s)	-32.	deg
Effective accelerating field ($E_0 T cos(\varphi_s)$)	~6	MV/m
Maximum surface field (E_{max})	<42.	MV/m
Kilpatrick limit (E_K)	26.	MV/m
Number of modules	7	
RF power/module	< 12.	MW
Length of bridge couplers between sections	$\frac{3}{2}\beta\lambda$	
Transverse focusing scheme	FODO	
Cavity bore radius (r_b)	1.5	cm

Table 1: Fixed Design Parameters and Design Choices

Energy out	401.3	MeV
Total length	59.6	m
Number of modules	7	
Number of sections/module	4	
Number of rf cells/section	16	
Total number of rf cells (7 × 4 × 16)	448	
Shunt impedance (ZT^2	36.6–48.2	MW/m
Transit time factor (T)	0.843–0.865	
E_{peak} @ E_o = 1 MV/m	4.62–5.08	MV/m
Gradient	8.04–7.07	MV/m
Long. phase ad./module	215–166	deg
Total RF power diss.	63.4	MW
Power budget, typical module		
copper loss	7.1	MW
beam power	2.0	MW
reserve and control	2.9	MW
Transverse focusing scheme	FODO	
Transverse phase advance/FODO cell	77–81	deg
Quadrupole magnetic length	8.0	cm
Quadrupole poletip field	6.3	kG
Quadrupole poletip radius (r_q)	3.0	cm

Table 2: Summary of Parameters for the 400 MeV Side-coupled Linac

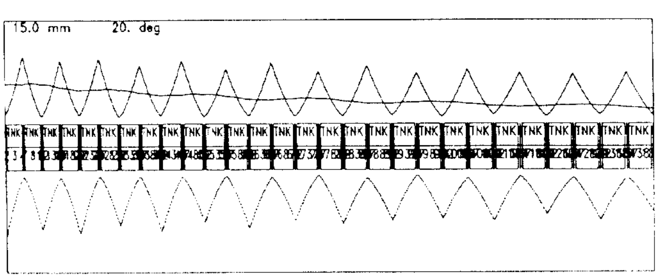

Figure 1: Beam envelopes through the side-coupled linac (horiz. and long. above, vert. below)

Kinetic energy	116.54	MeV
Beam current, averaged over pulse	50.	mA
Longitudinal emittance ε_L (90 %)	2.6	$\times 10^{-5}\pi$ eVs
Transverse emittance $\varepsilon_{x,y}$ in (90 %)	13.4	π mm mrad
Drift tube linac		
frequency	201.25	MHz
effective gradient E_0T (exit)	1.77	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)	6.81	MV/m
accelerating phase φ_s	-32.	deg
FODO half-cell (entrance)	164.0	cm
entrance aperture	1.5	cm
Matched waist		
β_x	1.06	m
β_y	8.65	m
β_φ @ 805 MHz	0.0131	deg/keV

Table 3: 116 MeV Matching Requirements

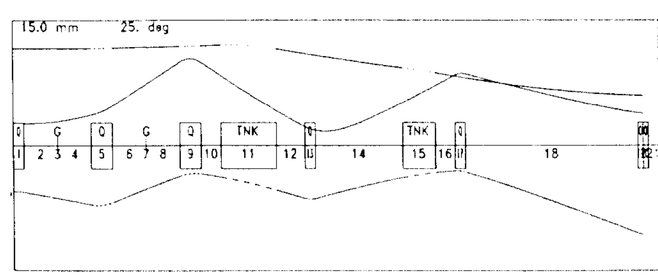

Figure 2: Beam envelopes in the 116 MeV matching section (horiz. and long. above, vert. below)