Reference Design for the Fermilab Linac Upgrade

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Introduction

Fermilab plans to increase the energy of its H^- linac from 200 to 400 MeV as part of a program to enhance the operation of the Tevatron for both collider and fixed target operation. The principal motivation for the linac upgrade is to reduce the incoherent spacecharge tuneshift at injection into the booster synchrotron. Other parts of the program are required to fully exploit the linac upgrade, but immediate improvement should be seen in booster performance with consequent benefit for collider luminosity and probably fixed target intensity as well. Improved diagnostic and beam steering capabilities and the elimination of some of the obsolete triode power amplifiers are expected to lead to improved reliability and consistency in linac operation. The upgrade design has been presented in a conceptual design report.[1] This paper treats the current evolution of the general design and principal parameters of the linac with little reference to components, supporting systems, conventional facilities, *etc.*

Initial Design Choices

The present 200 MHz drift tube linac consists of nine accelerating tanks. The last four tanks accelerate from 116.5 MeV to 200 MeV over 66 m. The proposed upgrade consists in replacing these tanks with 805 MHz high gradient structure to achieve 400 MeV in the same distance. The existence of suitable unused penetrations into the linac enclosure plus the assessment that klystrons of 10–15 MW capacity should be near the economic optimum has resulted in the choice to divide the structure into seven independently excited modules. The initial choices for the parameters to define an adequately constrained design problem are given in the Table. While informed by experience and intuition, some of these parameters are provisional and subject to modification depending on their consequences for the complete design.

The phasespace distribution of the beam at 116 MeV is not well known; it is inferred[2] from measurements at the end of 10 MeV tank 1 and at 200 MeV using PARMILA and imprecise data on quad strength and alignment in tanks 2–9. The design of the new linac must be compatible with any 116 MeV beam consistent with existing limited information. The transition section which provides both longitudinal and transverse matching between old and new linacs is treated in a companion paper.[3] It is basically an additional 805 MHz module serving as a buncher and transverse matching section; like the first accelerating module it is about 6 m long. With the matching provided by the transition section, the significant parameters defining the input beam are its kinetic energy, transverse emittance, and longitudinal emittance. These numbers reflect current operating experience; the emittances are expected to improve considerably as the result of a low energy upgrade[4] which is distinct from the project being described. However, the 400 MeV upgrade is intended to stand on its own and accept the 116 MeV beam that the present linac delivers.

Allowing for a transition section of 6 m and 2 m for modifications to the downstream transport line, the new linac must provide an average acceleration of $\Delta E/\Delta L$ = 283.5 MeV/ 58 m =4.89 MeV/m, considerably more than any operating proton or H⁻ linac. Achieving this gradient with acceptable operating reliability is the principal criterion for the design of the accelerating structure; achieving the gradient with satisfactory power economy places a premium on high shunt impedance. To maximize the shunt impedance the beam aperture has been chosen to be 1.5 cm radius, slightly smaller than the exit aperture of the source linac. The aperture choice in turn places emphasis on matching and optimum transverse focusing.

The choice of of -32° for the acceleration phase φ_s gives some tolerance for phase error but is not especially generous because the longitudinal emittance, determined by the 200 MHz capture, is large. The initial phase spread is $\sim \pm 20°$. Two other structure related numbers which are taken as initial choices are the limit E_{max} = 42 MV = 1.6 times the conventional Kilpatrick sparking limit on surface field[5] and total power per module < 10 MW. Experiments on RFQ sparker models[6] indicate that reliable operation and acceptable conditioning time can be obtained at such surface field with adequate care taken for surface quality and vacuum system. All of these three choices are in some measure arbitrary; they continue to appear appropriate as the design has become more complete.

Prototyping of both disk-and-washer[1] and side-coupled cavity[2] structures are in progress. For the purpose of making firm cost estimates and smaller extrapolations from current practice this reference design adopts a side-coupled structure derived from the LAMPF linac. To limit the phase shift and amplitude droop along the module, the rf power will be fed in at the center through an offset bridge coupler like that shown in Fig. 1. To maintain synchronism of the beam with the rf, such a coupler must be an odd multiple of $\beta\lambda/2$, where $\beta = v/c$ and λ is the free space wave length of the rf. Because the couplers also provide a place for transverse focusing, beam position monitors, *etc.*, they are designed for $3\beta\lambda/2$ to give adequate space at low β. Additional couplers of the same sort can be included in a module to provide for additional focusing as required.

Derived Parameters

Using the parameters of the 200 MeV prototype as a starting point, SUPERFISH was used to derive curves[7] shown in Fig. 2 for the effective shunt impedance ZT^2, transit time factor T, and peak surface field E_m normalized to 1 MV/m average axial field as functions of β for the full energy range. The effective shunt impedance values have been reduced by 12% to account for the effect of a 5% coupling slot and 3% to account for surface imperfection, brazed joints, *etc.* By assuming that each gap is excited so that the surface field is at its limit, these curves allow the calculation of the minimum number of gaps and length to obtain the required energy gain. One finds directly that it is not necessary to push the surface gradient to the limit and, on the contrary, the power limit can only be met by using practically all available length. At about the 5% level the required structure can be characterized very simply by $\Delta E/\Delta L$ =const. = 6 MeV/m, number of gaps per module = 60, power per module = 10 MW, average axial gradient E_0 = 8.1 MV/m, and E_{max} = 38 MV/m. This simple result implies that the parameter optimization should emphasize control of length and enhancement of ZT^2 even at the cost of some increase in E_{max}.

The constant $\Delta E/\Delta L$ model gives a starting point for a straight forward determination of approximate values for system length and

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[1] The DAW prototype has been developed in collaboration with Science Applications International Corp. and primarily fabricated by them.

[2] The SCS prototype has been developed in collaboration with Los Alamos Scientific Lab., and is being fabricated by them.

quad strength. With a constant number of cavities per module the module lengths increase in proportion to β. By requiring the inter-module spacing also to increase like β each rf power module can be a smoothly scaled version of the same basic beam optical system. An initial estimate of mechanical system requirements established $\sim$ 50 cm as a practical minimum spacing. This minimum is only slightly violated at 116 MeV by choosing $5\beta\lambda/2$ for the inter-module spacing.

A quick calculation of the minimum Twiss β attainable at the end of a module starting from a waist in the accelerating section one fourth of the module length away shows that no focusing scheme can keep the beam comfortably within the aperture of 1.5 cm radius without focusing in addition to that at the ends and at the central bridge coupler. Therefore, the modules are divided into four tanks by the addition of two more couplers at the one-quarter and three-quarter points. With this degree of segmentation a FODO focusing scheme is adequate. The length of the bridge couplers is sufficient to accommodate a doublet lattice for further reduction of the maximum beam width. However, a FODO lattice is the most forgiving of matching and alignment error and achieves the narrowest beam for a given $\int |B'|\, dl$; it is adopted for the reference design.

To simplify the structure somewhat the cavities within a single 15 cell tank are made all the same length $\bar{\beta}\lambda/2$ where $\bar{\beta}$ is calculated at the mean of the entrance and exit energies. Because the output energy depends on the cavity length, the energy gain for the tank has to be iterated to get a self-consistent $\bar{\beta}$ and E_{out}. An iterative calculation is also required to find E_0 to satisfy the $\Delta E/\Delta L$ = const. condition because for tanks with fixed cavity length the average accelerating phase $\bar{\varphi}_s$ is greater than the chosen $\varphi_s = -32°$ by an amount which changes with β.

By replacing the accelerating tanks in the first module by non-accelerating tanks ($\varphi_s = -90°$) having the same rf focusing strength and positioning them symmetrically between the quads, one can calculate a quad gradient that minimizes the maximum $\beta_{x,y}$ in the lattice. (All beam optical calculations have been made with TRACE-3D.[8]) The same $\hat{\beta} = \min\max \beta_{x,y} = 8.4$ m can be achieved when the tanks are placed as required by the bridge coupler lengths by adjusting the quad strengths and location of the quarter and three-quarter point quads. Alternatively, a slightly larger value of $\hat{\beta}$ can be accepted with one quad strength. The difference in beam width is only $\sim$ 5%. In either case the position of quads should be adjusted to maintain the waists at the center. The resulting layout is indicated on the beam envelope plot Fig. 3. The true minimum $\hat{\beta}$ is obtained with a phase advance per FODO cell of 79° including 10% spacecharge tune depression. Because this is approaching a stability limit[9] and because the minimum is quite broad the quad gradients were chosen to lower phase advance in the first module to 56°. As seen in Fig. 4, when this quad strength is used in the accelerating cells for the entire energy range the resulting beam envelopes are well matched. The $\hat{\beta}$ increases approximately as $\gamma = E/m_pc^2$ so that beam width varies as β^{-1}. Whether three different strengths are used or only one, the gradients for 8 cm quads are $\sim$ 21 T/m, a pole tip field of 4.2 kG for 2 cm aperture.

The axial field $E_0(\beta)$ which equalizes the power per module perturbs the pattern of rf defocusing resulting from the $\Delta E/\Delta L$ = const. rule. Additionally, although not necessarily, the value of E_0 has been taken to be constant over a module. If one ignores the difference from the $\Delta E/\Delta L$ = const. model and uses the same initial $\beta_{x,y}$ and focusing, the resulting beam envelope shows clear evidence of mismatch as shown in Fig. 5. Although the mismatch is quite possibly acceptable operationally, some quad trims are desirable.

The motive behind designing for one or few quad strengths was to make the use of permanent magnet quadrupoles (PMQ's) practical. There are two clear alternatives for combining trim capability with PMQ's: replace a fraction of them with pulsed electromagnetic quads to correct the match at a few points, or combine low current dc trim coils with most or all of the PMQ's. A realization of the second alternative using iron pole quads excited jointly by permanent magnet blocks and dc trim coils is being considered, but no choice has been adopted for the reference design. The conceptual design report used pulsed electromagnetic quads at all locations to establish the cost estimate.

Debuncher

The longitudinal phasespace area of the booster beam is proportional to the momentum spread of the beam from the linac because the beam debunches non-adiabatically before being captured by the booster rf. Thus, a debuncher is required. A suitable location has been found approximately 27 m downstream of the linac where the bunches have sheared to about $\pm 60°$. A tank of four $\beta\lambda/2$ cavities with an average gradient of 4.3 MV/m reduces the energy spread to $\Delta E < \pm 0.5$ MeV.[10]

Status of Upgrade Design Work

A detailed design and component specification process is underway, including rf structure prototyping and beam dynamics studies related to optimum focusing and tolerance for alignment, gradient, and phase errors. Papers on some details of this work are being presented at this conference.[11],[12],[13] The choice of rf structure will be made on the basis of power tests to be completed near the end of 1988. Once this choice has been made, it will be possible to focus on details of fabrication, mechanical systems, and beam dynamics with a well known set of rf structure properties. RF power supply development is proceeding more or less independently of other considerations except, of course, the total power estimates. The proposed schedule calls for a construction start in FY90 and completion in FY91. Prototype development is currently consistent with such a schedule.

Acknowledgements

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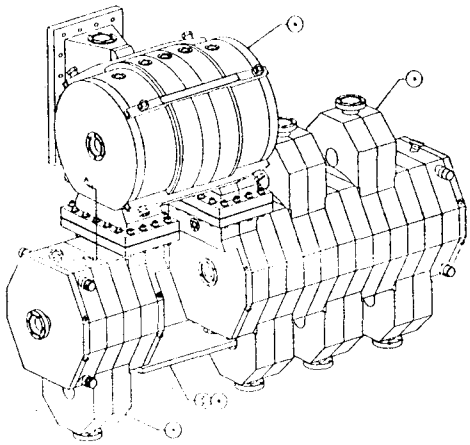

Figure 1: Side-coupled accelerating structure and $3\beta\lambda/2$ bridge coupler, isometric view (LASL drawing)

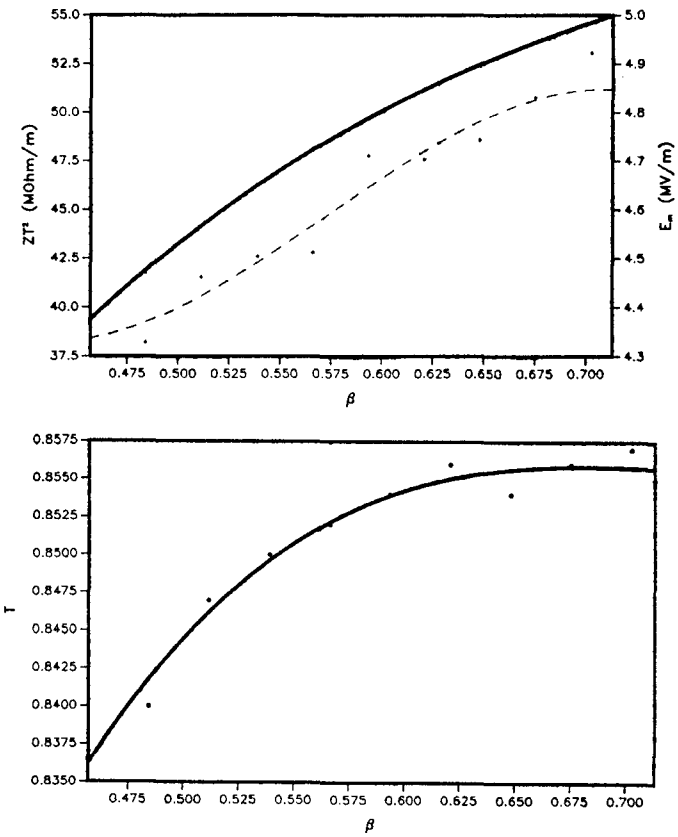

Figure 2: Effective shunt impedance ZT^2 and E_m, maximum surface field for 1 MV/m axial field, (above) and transit time factor T (below) as functions of β

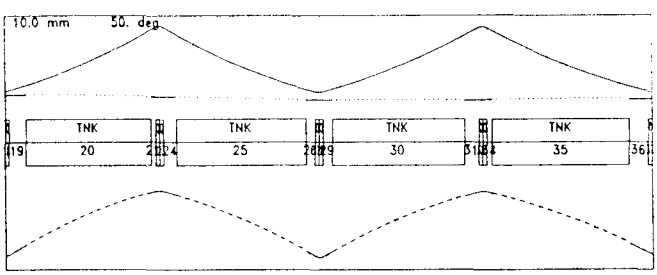

Figure 3: One module of linac structure consisting of two FODO focussing cells

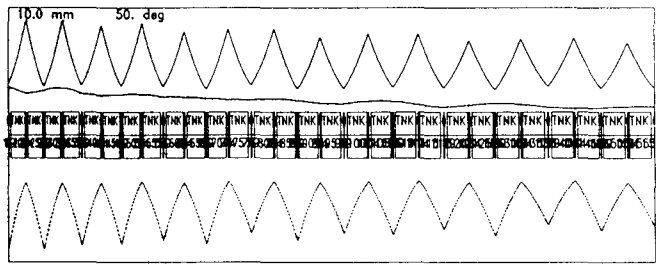

Figure 4: Beam envelopes of $\Delta E/\Delta L$ =const. linac with three different quad strengths

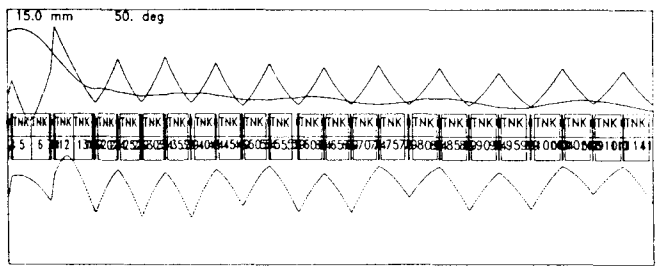

Figure 5: Beam envelopes of linac with power optimized rf gradients using untrimmed values of quads found for $\Delta E/\Delta L$ = const.

Kinetic energy in	116.54	MeV
Kinetic energy out	400.	MeV
Length	< 55.	m
Longitudinal emittance ε_L (90 %)	6.2 $\times 10^{5}$	π eVs
Transverse emittance $\varepsilon_{x,y}$ (90 %)	10.	π mm mrad
Beam current, averaged over pulse	50.	mA
Frequency of rf	805.0	MHz
Kilpatrick limit on surface field E_K	26.	MV/m
Maximum surface field $E_m(1.6E_K)$	42.	MV/m
Accelerating phase φ_s	-32.	degree
Number of modules	7	
RF power/module	~10.	MW
RF pulse length	< 100.	μs
Repetition rate	15.0	Hz
Cavity bore radius	1.5	cm
Quadrupole poletip radius	2.0	cm

Table 1: Design Criteria and Initial Parameter Choice