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400-MEV UPGRADE FOR THE FERMILAB LINAC

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Abstract Fermilab plans to upgrade the Tevatron to expand the physics research program in both the fixed target and the collider operating modes. The first phase of this program is to increase the energy of the H^- linac from 200 to 400 MeV in order to reduce the incoherent space change tuneshift at injection into the Booster which can limit either the brightness or the total intensity of the beam. The linac upgrade will be achieved by replacing the last four 201 MHz drift-tube tanks, which accelerate the beam from 116 to 200 MeV, with seven 805 MHz side-coupled cavity modules operating at an average axial field of about 8 MV/m. This will allow acceleration to 400 MeV in the existing Linac enclosure.

INTRODUCTION

The Fermilab 200-MeV linear accelerator has operated almost continuously since 1970 as an injector for the Fermilab chain of accelerators and as a secondary neutron producer for the Neutron Therapy Facility with a reliability approaching 99%. The purpose of the Fermilab Linac Upgrade is to increase the final kinetic energy of the Linac beam from 200 MeV to about 400 MeV. This is expected to reduce beam emittance degradation in the 8 GeV Booster following the Linac and allow beams of higher brightness (number of particles per unit emittance) to be accelerated.[1] The intended consequences of this will be to increase the collision rate in the antiproton-proton collider and the intensity for the fixed target experiments.

The present 200 MeV drift-tube linac (DTL) consists of nine accelerating cavities operating at a frequency of 201.25 MHz. The Upgrade project will replace the last four cavities, which accelerate the beam from 116 MeV to 200 MeV in a length of 66 m, with seven coupled cavity modules operating at a frequency of 805 MHz or four times the DTL frequency. The higher frequency allows higher accelerating gradients to be achieved so that a kinetic energy of 400 MeV can be reached in the same 66 m length. Each module will be driven with a klystron-based rf power supply rated to deliver 12 MW.

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ACCELERATING STRUCTURE

The side-coupled accelerating structure (SCS) has been selected for the Linac Upgrade because it is well understood and fully proven. From the work done at Los Alamos National Laboratory on the SCS and the Fermilab design and modelling effort, we have confidence that our performance goals can be met.

Because the 400-MeV linac is to replace that part of the existing 200 MHz drift-tube linac which accelerates the beam from 116 MeV to 200 MeV, it must have a high gradient and make conservative use of space for matching, focusing, mechanical systems, etc. In particular, a transition section for matching the beam between the old and new accelerators and a space of about two meters at the downstream end of the new linac for changes in the Linac-to-Booster transport line are required. Other major design goals are to minimize power consumption and to keep all parameters within a range favoring dependable routine operation. Table I summarizes the principle design criteria and parameters.

Table I Design criteria and general parameters

Initial kinetic energy (T_i)	116.54	MeV
Final kinetic energy (T_f)	401.56	MeV
Length, including transition section	64.300	m
Frequency of rf	805.0	MHz
Beam current averaged over pulse (I_b)	50.	mA
Beam pulse length	<100.	μs
Repetition rate	15.0	Hz
Accelerating phase (ϕ_s)	-32.	deg
Average axial field (E_o)	8.04-7.07	MV/m
Maximum surface field (E_{max})	37.1	MV/m
Kilpatrick limit (E_k)	26.	MV/m
Number of modules	7	
RF power/module, typical	<12.	MW
copper loss	7.1	MW
beam power	2.0	MW
reserve and control	2.9	MW
Number of sections/module	4	
Number of rf cells/section	16	
Total number of rf cells (7x4x16)	448	
Length of bridge couplers between sections	$3\ \beta\lambda/2$	
Transverse focusing scheme	FODO	
Transverse phase advance/FODO cell, average	79.	deg
Quadrupole magnetic length	7.0	cm
Quadrupole poletip field	5.26	kG
Quadrupole bore radius	2.0	cm
Cavity bore radius	1.5	cm

The accelerating gradient (average axial field, E_o) of 8 MV/m is more than three times the gradient of the existing DTL. Long voltage conditioning times and an inordinately high sparking rate causing erratic beam pulses and unreliable injector operation are considered unacceptable for the new linac. To investigate these constraints, a high power model of the SCS consisting of separate six and two cell sections connected with a bridge coupler has been constructed in a collaboration between Fermilab and Los Alamos National Laboratory (Figure 1). This model has demonstrated that after an initial conditioning period of about 6 million rf pulses the operating gradient for the design can be achieved with a spark rate that when normalized to the full SC linac (at 15 Hz and 120 μsec pulse length) would result in less than 1 spark per 100 rf pulses. Since this is considered somewhat higher than desirable, a further optimization of the cell geometry has been done. The peak surface fields have been reduced by about 6% and the high field surface area by about 50% with only a 2% reduction in the effective shunt impedance. The sparking rate should be reduced by about a factor of four.

REFERENCE DESIGN

The design to meet the criteria and general parameters of Table I is reasonably well advanced[2]. The division of the Linac into seven independently excited rf modules results from three principle considerations, namely the practical size for 805 MHz klystrons, the shunt impedance of the structure, and the existence of suitable penetrations from the equipment gallery into the linac vault for the waveguides. Uniform distribution of the rf power favors feeding the modules from the center, so there is a bridge coupler at a location which can also accommodate a quadrupole. RF defocusing requires that the quadrupoles of the FODO channel be less than two meters apart in the first modules. Symmetry with respect to the rf feed point requires an even number of sections per module. These conditions are satisfied by dividing the modules into four sections separated by bridge couplers of length $3\beta\lambda/2$ (Figure 2). For the bridge coupler, we have adopted the five-post design developed at LANL for the LAMPF accelerator.[3] There are sixteen accelerating cells per section.

The overall character of the focusing scheme follows from the appropriate distance between elements established for the first module, the lattice type selected, and the sequence of module lengths resulting from the requirement for the same rf power per module. A FODO focusing scheme has been adopted for the Linac Upgrade. The circumstance that the power distribution is optimized with an equal number of accelerating gaps in each module results in a module length increasing smoothly with energy. The focusing is naturally strongest at the low energy end because the maximum of the transverse β-function (envelope width function) depends primarily on the length of the focusing cells and only weakly on the strength of the focusing quadrupoles. For each choice of quadrupole spacing there is a particular β_{min}, the width Twiss parameter at the waist, for which the beta function at the quadrupole, β_{max}, has its minimum value. The values β_{min} and β_{max} can be used as fitting conditions at the beam waists along the structure to determine the required quadrupole strengths. Because the optimum power distribution for the SC structure leads to a fixed number of cells per section, the section lengths increase smoothly with energy, and the same β_{min}, β_{max} pair can be used for all focusing cells. For quadrupoles of 7 cm magnetic length with a 2 cm aperture and pole tip fields of approximately 5 kG the phase advance is in the range of 77 to 80 degrees and β_{max} is minimized at the low energy end. Because the low energy modules are shorter, four sections per module are sufficient to get the required quadrupole spacing at low energy. The same subdivision suffices at higher energy because the rf defocusing decreases sufficiently.

Figure 3 shows the beam envelopes along the linac in all the planes on the basis of the parameters in Table I. In the figure, the horizontal and longitudinal envelopes are shown above the section layout and the vertical plane envelope is shown below. This figure was calculated by the program TRACE 3-D which takes account of rf defocusing and space charge in a linear approximation.[4] Particle dynamics calculations have been made which verify the TRACE 3-D results.

The DTL operates with stronger transverse focusing and weaker longitudinal focusing than the SCL. Therefore, six-dimensional phase space matching is required to preserve the brightness of the input beam in the new linac. The longitudinal matching is effected by placing a five-cell 805 MHz buncher immediately after the last drift-tube tank and a three-cell vernier buncher about one third of the way along the bunching drift space for additional matching. The transverse matching requires at least four quadrupoles to control the phase ellipse parameters in both horizontal and vertical coordinates. A fifth quadrupole is provided to extend the range of matching capability to help control the width of the beam envelope in the transition section. The total length of the transition section is about four meters.

STATUS

At the present time a prototype module, the first module of the required seven, is being designed and fabrication of one section has started. A 12 MW prototype klystron is nearing completion and is scheduled to be tested in October. In about one year the klystron and the module will be mated and testing will start. It is anticipated that the other systems will be fabricated in an orderly manner starting in 1990.

ACKNOWLEDGEMENTS

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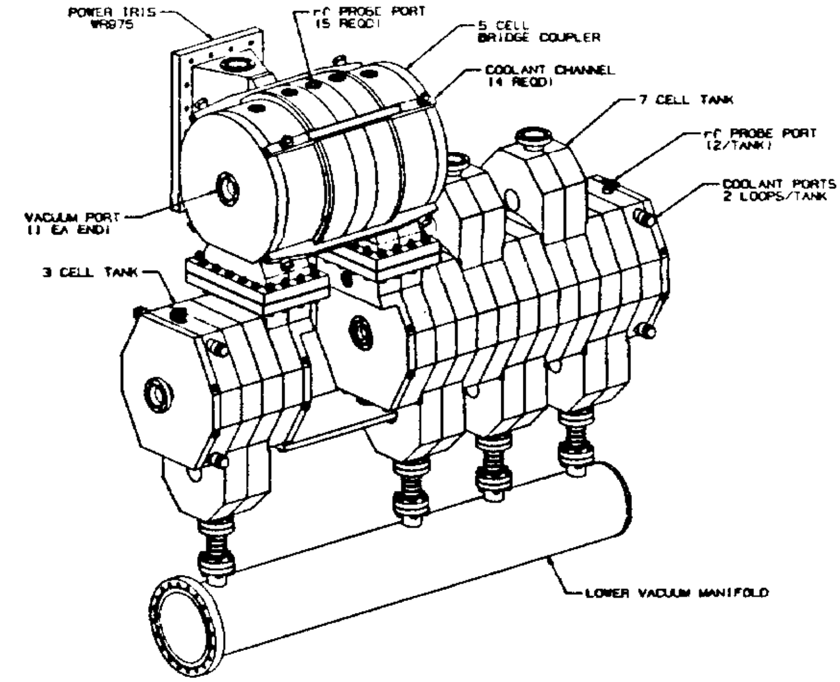

Figure 1 Power model of side-coupled structure with bridge coupler

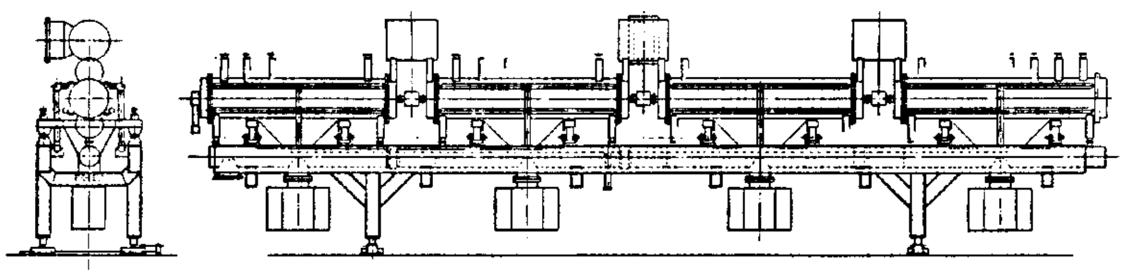

Figure 2 SCS module of four sections with bridge couplers

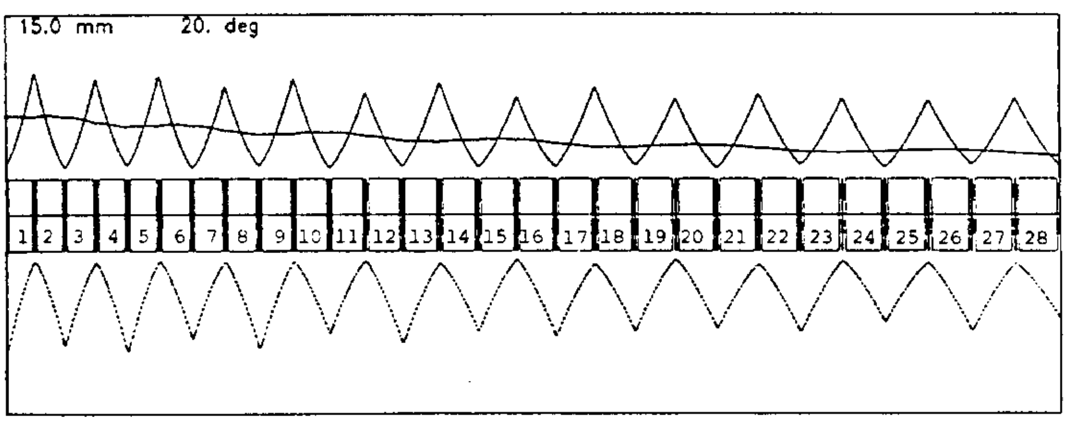

Figure 3 Beam envelopes for the horizontal, longitudinal and vertical motion (lower trace)