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The 400 MeV Linac Upgrade at Fermilab

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THE 400 MEV LINAC UPGRADE AT FERMILAB

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Abstract

The Fermilab Linac Upgrade is planned to increase the energy of the H- linac from 200 to 400 MeV. This is intended to reduce the incoherent space-charge tuneshift at injection into the 8 GeV 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 201.25 MHz drift-tube linac (DTL) 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 7.5 MV/meter. This will allow acceleration to 400 MeV in the existing Linac enclosure. Each accelerator module will be driven with a 12 MW klystron-based rf power supply. Three of seven accelerator modules have been fabricated, power tested and installed in their temporary location adjacent to the existing DTL. All seven RF Modulators have been completed and klystron installation has begun. Waveguide runs have been completed from the power supply gallery to the accelerator modules. The new linac will be powered in the temporary position without beam in order to verify overall system reliability until the laboratory operating schedule permits final conversion to 400 MeV operation.

Introduction

The present 200 MeV drift-tube linac (DTL) consists of nine accelerator cavities operating at a frequency of 201.25 MHz. Each cavity is powered by a triode-based radio-frequency (rf) power supply rated to deliver up to 5 MW of peak power for a 125 μsec flat-top pulse. The Linac Upgrade will replace the last four cavities, which accelerate the beam from 116 MeV to 200 MeV in a length of 66 meters, with seven side-coupled cavity modules operating at a frequency of 805 MHz or four times the DTL frequency (see Figure 1). The higher frequency allows higher accelerating gradients to be achieved so that a kinetic energy of 400 MeV can be reached in the same linac enclosure. Each module will be driven with a klystron-based rf power supply rated to deliver up to 12 MW of peak power for 125 μsec at a 15 Hz repetition rate. The nominal peak power requirement of each module with 35 mA of beam is about 10 MW. The status of the Linac Upgrade through 1990 was reported in Ref. 1.

Accelerator Structure

The side-coupled (SC) accelerating structure was selected for the Linac Upgrade because it is well understood and fully proven. The side-coupled structure was used above 100 MeV for the 805 MHz Los Alamos Meson Physics Facility (LAMPF) proton linac designed in the early 1960's (see Figure 2). This coupled-cavity structure is operated in a so-called TM_{010} $\pi/2$ standing wave mode in which the phase shift between an accelerating cell and an adjacent coupling cell (off the beam axis) is 90 degrees. The accelerator cell length is $\beta\lambda/2$ for particle-wave synchronism. Here β is the particle velocity divided by the speed of light, and λ is the free space wavelength of the accelerating field. The insensitivity of field amplitudes and phases to mechanical perturbations in such $\pi/2$ structures is a fundamental reason for their widespread use.

Because the new side-coupled linac will replace that part of the existing drift-tube linac which accelerates the beam from 116 MeV to 200 MeV, it must have a gradient about three times higher than in the DTL and make conservative use of space for beam matching, focusing and diagnostics. In particular, a 4-meter Transition Section (two 805 MHz buncher cavities and quadrupoles) for matching the beam between the DTL and side-coupled linac and a space of about two meters at the downstream end of the linac for changes in the Linac-to-Booster transfer line are required. Table 1 summarises the principle design criteria and derived parameters for the new linac.

The division of the new SC linac into seven independently excited rf modules originally resulted from three principal considerations, namely the practical size for 805 MHz klystrons, the shunt impedance of the structure and the existence of suitable penetrations from the linac utility basement into the linac enclosure. Since the original design in 1987, radiation safety considerations have mandated the need for new waveguide penetrations with the existing downstream DTL penetrations in the linac utility

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basement to be ultimately sealed. Uniform distribution of rf power favors feeding the modules from the center, so there is a bridge coupler at that location which can also accommodate a magnetic quadrupole. Rf defocusing requires that the quadrupoles of the FODO channel be less than two meters apart in the first modules. These conditions were satisfied by dividing the modules into four sections separated by bridge couplers of length $3\beta\lambda/2$ (see Figure 3). The post-stabilized bridge-coupler developed for LAMPF was used for the Fermilab Linac.

Table 1. 400 MeV Linac Design Criteria and General Parameters

Initial kinetic energy (T_i)	116.54	MeV
Final kinetic energy (T_f)	401.46	MeV
Length, including transition section	63.678	m
Frequency of rf (f)	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)	8.07–7.09	MV/m
Maximum surface field (E_{max})	36.8	MV/m
Kilpatrick limit (E_K)	26.	MV/m
Number of modules	7	
RF power/module, typical	< 12.	MW
copper loss	7.2	MW
beam power	2.0	MW
reserve and control	2.8	MW
Number of sections/module	4	
Number of rf cells/section	16	
Total number of rf cells (7 × 4 × 16)	448	
Length of bridge couplers between sections	$\frac{3}{2}\beta\lambda$	
Transverse focusing scheme	FODO	
Transverse phase advance/FODO cell, average	79.	deg
Quadrupole magnetic length	8.0	cm
Quadrupole poletip field	4.6	kG
Quadrupole bore radius (r_q)	2.0	cm
Cavity bore radius (r_b)	1.5	cm

The average axial field, E_o of 7.5 MV/m in the new linac is about three times the gradient in the existing DTL. Early in the project it was considered desirable to limit the spark rate to about one spark per thousand rf pulses corresponding to 0.1% beam loss due to cavity sparking. Re-evaluation of earlier 16-cell prototype power test results[2] indicated that a spark rate of about 0.1% could be expected for 60 μsec pulse lengths (15 Hz repetition rate). Between June 1991 and March 1992, all seven accelerating modules were voltage conditioned in a concrete cave to shield bremsstahlung x-rays. A prototype Litton L-5859 klystron was used to power the modules. This 12 MW klystron continues to operate satisfactorily after nearly 6000 hours of high-power output.

All accelerator modules were conditioned until their spark rate, extrapolated to a full linac, was lowered to 0.2% at 60 μsec pulse length. Only 30 μsec of beam must be accelerated in operation. Further voltage conditioning is expected during linac operation. For pulse lengths, τ between 40 μsec and 120 μsec the spark rate varied like τ^3. The reason for this strong dependence has not been determined. Inspection of conditioned cavities indicated that sparking had occurred on the side-cell and accelerating-cell nose cones as well as the coupling slot corners. No change in coupling constant could be detected. The pressure in conditioned cavities under full power was about 10^{-8} torr. Multipactoring at discrete low-power levels (< 5 MW) was suggested by higher pressure levels (10^{-7} torr). No multipactoring was evident in the expected operating range above 9 MW.

Radio-Frequency Power System

The 805 MHz Linac Upgrade requires seven high-power klystron and modulator systems to run the seven independent accelerator modules. Table 2 gives a complete power tabulation for an RF station assuming 35 mA of accelerated beam. This shows that only about 10 MW of peak power is needed. The klystron specifications in Table 3 apply to the L-5859 12 MW klystrons being produced by Litton Electron Devices. The RF modulator built by Fermilab consists of a pulse forming network (PFN) discharged into the klystron cathode through an oil-filled 20:1 step-up transformer. The PFN is charged to 18 kV from a power supply using the resonant charging technique (capacitor and charging choke) with an SCR (silicon controlled rectifier) switch to initiate the charging cycle. The power supply stores about 40 kJ but only about 6 kJ are used to charge the PFN every 66 msec (15 Hz).

Table 2. RF Power Tabulation

Nominal power, accelerating 35 mA beam (SUPERFISH shunt impedance derated by 15%)	8.6 MW
Waveguide run losses (WR975), harmonic isolator (if required)	0.6 MW
Add 10% for feedback loop regulation	0.9 MW
The cavity diameter may have to be altered slightly at some β's to avoid TM_{110} deflecting modes	0.1 MW
Estimated Total	10.2 MW

The modulator consists of three units and is discussed in detail in Ref. 3. The schematic in Figure 4 shows the 100 kW charging supply, the 26-cell PFN and the step-up transformer that make up the circuit. In operation, the charging supply maintains a 9 kV output voltage on its filter bank. When the charging supply SCR switch is fired, the choke resonates with the PFN capacitors and charges them to 18 kV. The PFN SCR switch is then fired to discharge the PFN into the pulse transformer primary. The reflected load of the klystron matches the 3 Ω characteristic impedance of the PFN and the primary sees a 9 kV/3 kA square wave pulse for 125 μsec. The secondary pulse delivered to the klystron is 180 kV and 151 A with a flatness and regulation of ±0.05%. Klystron power output versus input drive power is shown in Fig. 5.

Table 3. Klystron Specifications

Peak power output	12 MW
Pulse length	125 μs
Pulse repetition rate	15 pps
Duty factor	0.1875%
Average power	22.5 KW
Efficiency	50%
Gain	50 dB
RF output	WR975 waveguide
Dimensions	108 inch height 24 inch diameter
Voltage	170 KV
Current	141 A

Project Status

The three major systems for the Linac Upgrade are side-coupled accelerator modules, rf modulators and 12 MW klystrons. The Project began construction in October 1989 and is scheduled for linac conversion to 400 MeV energy in the spring of 1993 based on the present laboratory operating schedule.

Fabrication of a prototype accelerator module (four sections and three bridge couplers) began in October 1989. This prototype was electrically and mechanically equivalent to the first of seven side-coupled linac modules needed for the new linac. The first 16-cavity section was brazed at Pyromet Inc. (San Carlos, California) in January 1990 and the second section in April. The third and fourth sections were brazed simultaneously in August 1990.

Final tuning of the prototype module was completed in March 1991. The power testing was done in June and July 1991. Some polishing of bridge coupler flanges and the addition of improved RF seals were done to reduce arcing across the flanges. This prototype module then was judged adequate to become Module 1 of the new linac.

In June 1990 Class 1, OFHC copper segments for production accelerator fabrication began arriving from Hitachi Industries, Japan. Copper for one 16-cavity linac section arrived every two weeks to begin a four-month machining, tuning and brazing cycle. The segmented construction of the side-coupled accelerating structure used at LAMPF was adopted for the Fermilab linac (see Figure 6). Two sections were brazed every month at Pyromet Inc. starting in November 1990.

The brazing of accelerator sections was carried out with a 100% success rate with no braze date ever missed during the thirteen month schedule. Brazed sections were tuned individually to 805 MHz, mated in pairs to their bridge couplers for tuning, and finally connected by the center-feed bridge coupler for final module tuning (see Refs. 4&5). Accelerator modules were then voltage conditioned as described earlier with 20 to 30 million RF pulses to reduce their spark rate. In the four-day period of March 10-13, 1992 all seven modules and the transition section were placed in the linac enclosure adjacent to the present drift-tube linac.

The 12 MW klystrons to power the new accelerator modules are being produced by Litton Electron Devices (San Carlos, California). The L-5859 klystron has five cavities (input, two idlers, penultimate, output) and operates at 2 μperv. Eight production klystrons have been delivered at the rate of one per month since in November 1991. A total of 14 tubes are on order and should all be delivered by February 1993.

Three of the seven 12 MW RF modulators have been commissioned and installation of tested klystrons has begun. The remaining four modulators are 90% complete. As klystrons are installed, completed RF systems will be operated and accelerator modules powered in the linac enclosure to verify overall system reliability.

References

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[4] H.W. Miller, Zubao Qian, R. Padilla, T.G. Jurgens, "Tuning Summary for the 805 MHz Side-Coupled Linac in the Fermilab Linac Upgrade", 1992 Linac Conf., these proceedings.

[5] Z. Qian, M. Champion, H.W. Miller, A. Moretti, R. Padilla, "Final Module Tuning of the 805 MHz Side-Coupled Cavities in the Fermilab Linac Upgrade", 1992 Linac Conf., these proceedings.

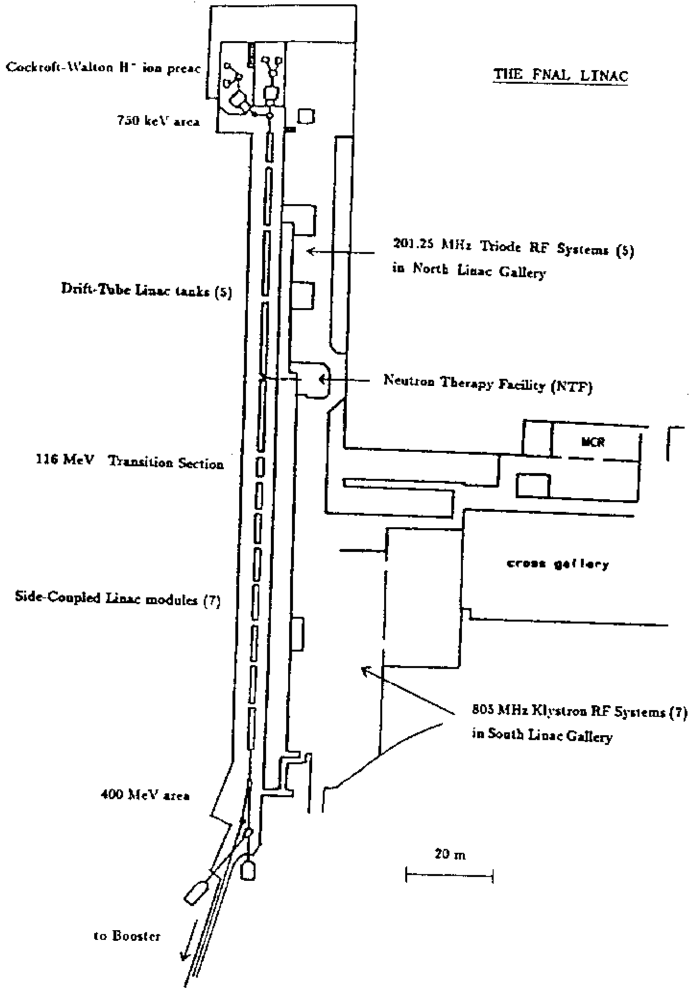

Figure 1. The Fermilab Linac (plan view).

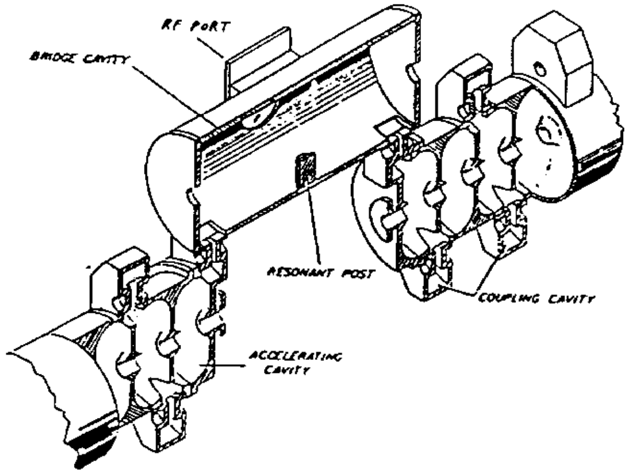

Figure 2. The LAMPF side-coupled accelerator and post-stabilized bridge coupler.

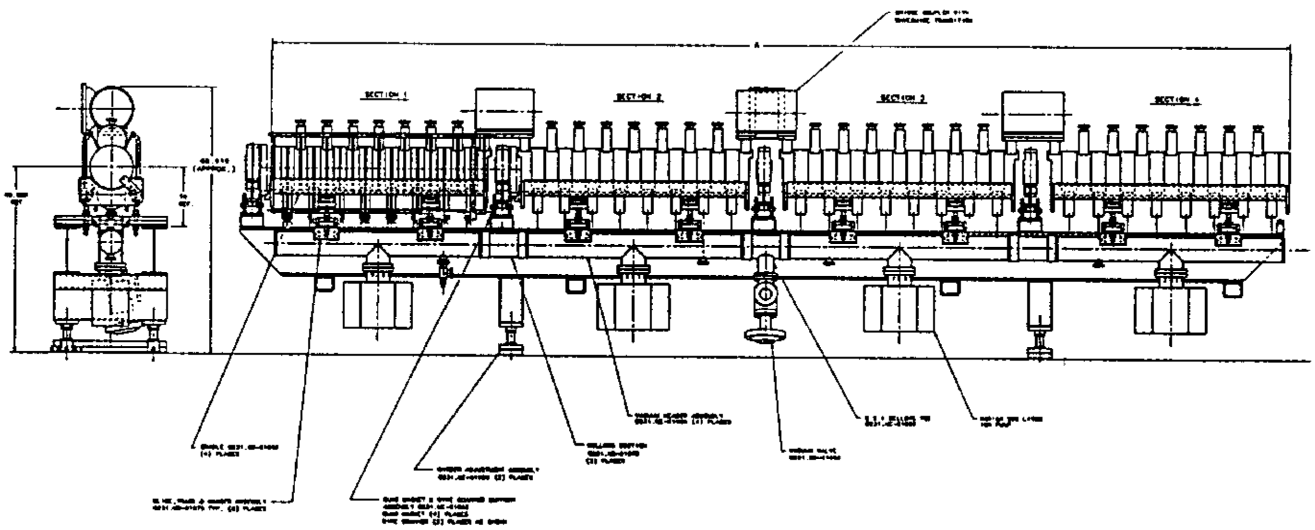

Figure 3. Fermilab side-coupled accelerator module containing four sections and three bridge-couplers. Module height is two meters and the length varies from 6.5 to 10 meters for Modules 1 to 7.

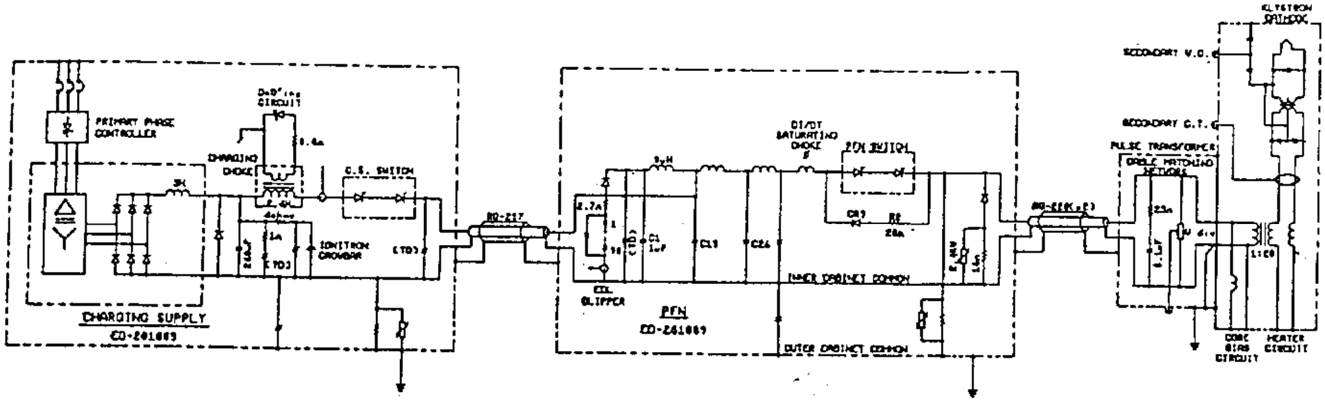

Figure 4. Charging supply, PFN and pulse transformer.

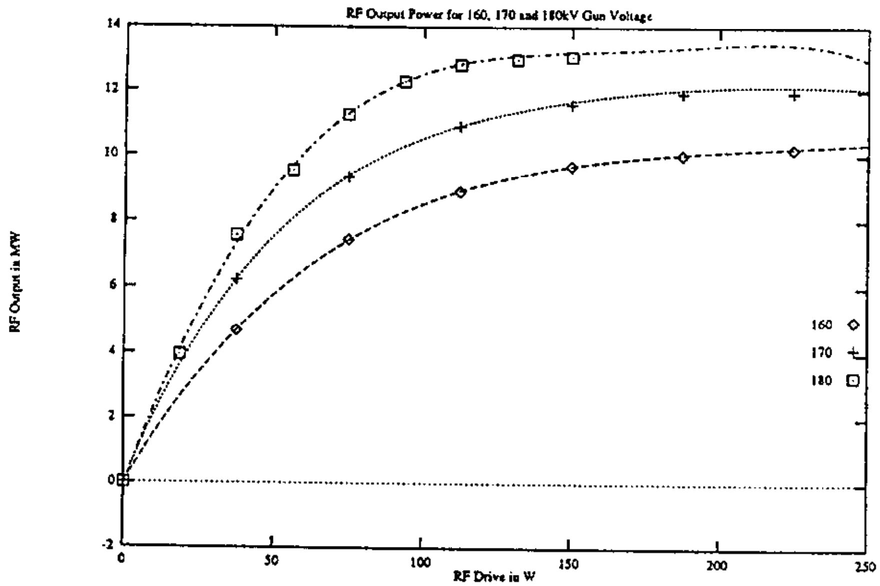

Figure 5. RF power output versus input drive power at different gun voltages for the Litton L-5859 805 MHz klystron.

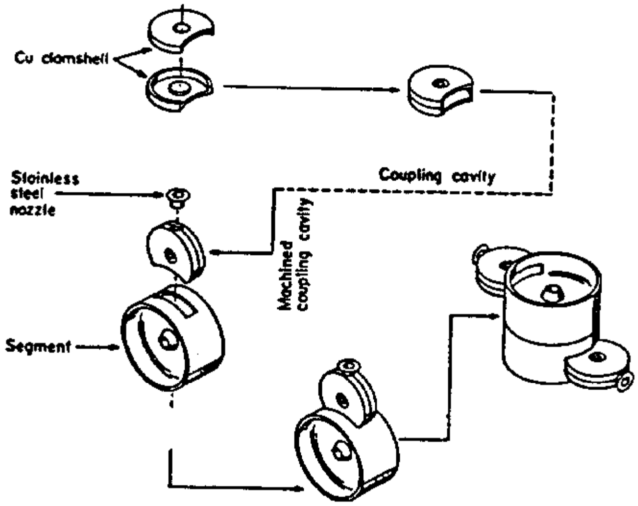

Figure 6. Segmented construction of side-coupled linac used for LAMPF and Fermilab.