Fault-Tolerant Superconducting Linac Design for a 5-MW Neutron Spallation Source*

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Abstract

An 805-MHz superconducting linac is proposed, which could accelerate protons from 0.1 to 2.0 GeV in less than 730 m for a peak surface field in the cavities of 17 MV/m. The linac would furnish 5 MW of beam for a neutron spallation source, plus up to 10 additional MW of beam for other purposes. The design uses 454 elliptical cavities arranged in twelve groups, identical cavities being used within each group. Characterization of elliptical cavities for betas from 0.44 to 0.94 and the steps of the design procedure are presented. The effective peak power fed by each rf coupler would be less than 100 kW for all of the cavities. 6.5 kW of power at 2 deg K would need to be extracted by the cryogenic system. Space charge was found to have a negligible effect on emittance growth. The design is such that one cavity per group could be inoperable, and the gradient in the remaining cavities could be increased to compensate. The longitudinal and transverse acceptances of the linac would not be significantly degraded under such fault conditions. A corresponding 402.5-MHz linac design is being developed.

Introduction

We consider the high-energy linac design for a proposal to upgrade the LAMPF linear accelerator facility to drive a 5-MW spallation neutron source for material science studies and to provide additional intense beams for nuclear physics or other purposes. The proposal envisions replacing the present linac with an accelerator to supply an accumulator ring with 2.5 mA average current of protons at 2.0 GeV for the spallation neutron source, and to provide up to 5.0 mA of protons at 2.0 GeV for other uses. We propose using a superconducting linac with elliptical cavities for acceleration from 0.1 to 2.0 GeV. This linac section would occupy less space than the present LAMPF coupled-cavity linac, which accelerates protons from 0.1 to 0.8 GeV in 730 m. (The portion of the accelerator that brings the protons to 0.1 GeV might also use some superconducting components, but we will not consider that part of the facility in this article.)

In the following, we characterize the performance of elliptical cavities for the needed range of relativistic velocity beta, develop a fault-tolerant reference design for a superconducting linac for 805 MHz, and present the calculated performance of such a linac. We are also in the process of developing a corresponding 402.5-MHz linac design.

Elliptical Cavity Characterization

In accelerating from 0.1 to 2.0 GeV, we go through about a 2:1 range in relativistic particle velocity β (0.428 to 0.948) and a 6:1 range in relativistic momentum $\beta\gamma$ (0.47 to 2.97). The cavity geometry changes to approximately

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match β as the particles accelerate, and some transverse focusing properties change as $\beta\gamma$.

The cross section of half of one cell of an elliptical cavity consists of two arcs (which approximate an elliptical nose) at the entrance of the cell, a sloping line, and a circular dome coming up to the major diameter of the cell, as in Fig. 1. We found the cavity proportions change drastically over the desired velocity range, as shown in Fig. 2. For design purposes, we would like to know the ratios of peak electric and magnetic fields on the cavity surface to the accelerating field, E_{max}/E_0T and H_{max}/E_0T, and the ratio of shunt impedance to cavity Q, ZT^2/Q. We found that these parameters change significantly over the desired velocity range as well. In order to characterize their behavior, we have found optimized geometries for betas of 0.5, 0.6, 0.7, 0.8, and 0.9 using SUPERFISH calculations. We then found approximate equations for the desired parameters as a function of beta.[1] We chose geometries that gave a cell-to-cell coupling of 3%, which is large enough that the field distributions in cavities of up to 7 cells will be stable with reasonable tuning errors present. The results of this analysis are as follows:

$$E_{max}/E_0T = 9.77 - 14.82\,\beta + 6.93\,\beta^2\,, \qquad (1)$$

$$H_{max}/E_0T = (1000)(22.7 - 42.3\,\beta + 24.4\,\beta^2)\,, \qquad (2)$$

and

$$ZT^2/Q = (f/805)(-225.50 + 782.66\beta - 327.27\beta^2)\,, \qquad (3)$$

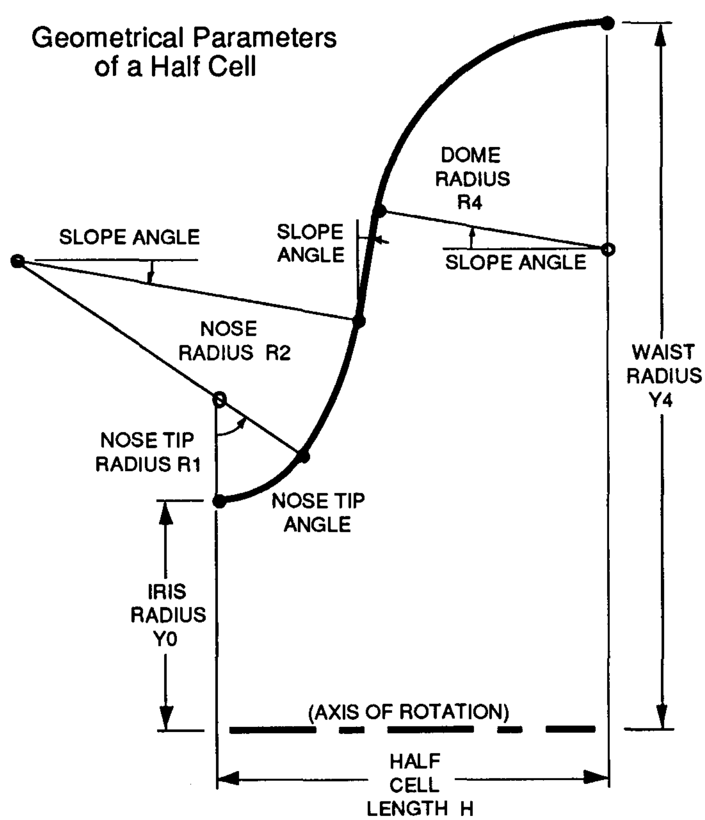

Fig. 1. Geometrical parameters for half of one cell of an elliptical superconducting cavity.

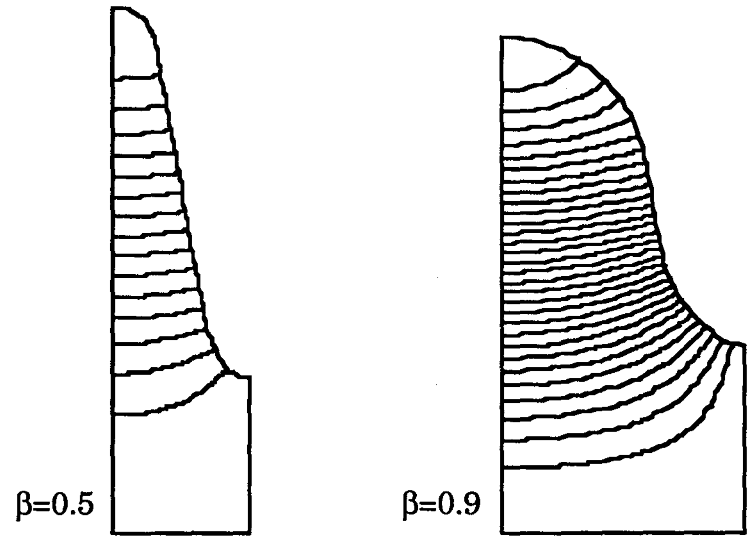

Fig. 2. Cavity shape and electric field lines for half cells for beta=0.5 and beta=0.9 (from SUPERFISH computer code).

where H_{max} is in amperes/m for E_0T in MV/m, f is the rf frequency in MHz, and ZT^2 is the shunt impedance in ohms/m. We use the circuit convention, in which $ZT^2 = (E_0TL)^2/(2PL)$, for a cavity of length L dissipating a power P.

We have also given initial consideration to damping the higher-order modes (HOMs) of such superconducting cavities.[1] The values of the external Qs that we calculated were low enough that we do not anticipate any severe difficulties in adequately damping the HOMs.

Our linac designs envision sections using a fixed-cavity geometry for some number of cavities. This simplifies design and fabrication, and opens the possibility of having spare cavity units on hand to facilitate repairs. Thus, we need to know how to calculate cavity performance when the particle velocity is not exactly at the design velocity of the cavities.

For elliptical superconducting cavities, the accelerating field has a variation with longitudinal position that is approximately a half sinusoid over the cell length. This means that the field acts over the full cell length, and not just over the length of some accelerating gap, as in some other cavity types. We found [2,3] that for the elliptical cavities, the ratio of the transit time factor T for a relativistic velocity β is related to the transit time factor T_d for the design velocity β_d by

$$\frac{T}{T_d} = \frac{\sin(\frac{1}{2}\pi d)}{(1 + 0.5d)(\frac{1}{2}\pi d)}, \tag{4}$$

where

$$d = \frac{\beta_d}{\beta} - 1 . \tag{5}$$

We use the convention that the design velocity β_d is such that the particle traverses a distance of $\beta_d\lambda/2$ in half an rf period, where λ is the rf wavelength.

When the velocity is at design, $\beta = \beta_d$, $d = 0$, and $T = T_d$. There is also an effect on the transverse momentum change in passing though one accelerating cell:

$$\Delta p_r c = -2hq\, E_0 T\, \gamma_w\, I_1(k_w r_c) \cdot \frac{1 - \bar{\beta}\beta_d + d}{\bar{\beta}} \sin \phi_c \, , \tag{6}$$

with
$$\gamma_w = (1 - \beta_d^2)^{-0.5} \, , \tag{7}$$

$$k_w = \frac{\omega}{\beta_d\, \gamma_w\, c} \, , \tag{8}$$

and where Δp_r is the momentum impulse, c is the velocity of light, h is half the cell length, q is the particle charge in units of e, E_0T is the accelerating field with T being the generalized transit factor given in Eq. (4), I_1 is the modified Bessel function of order 1, r_c is the radial distance of the particle from the beam axis, and ϕ_c is the rf phase at angular frequency $\omega = 2\pi f$ when the particle reaches the center of the cell. We note that Eq. (6) is the same as the equation for the case when the velocity is at design, except for the presence of the d term, and T being given by Eq. (4).

We have incorporated the effects given in Eqs. (4)-(6) in the computer code LIND3 for tracking one particle and the code SIMALAC for tracking many particles. We were then able to generate universal curves of relative acceleration vs relative beta, as shown in Fig. 3. These curves are good for any elliptical or other cavity for which the longitudinal electric field varies as $\cos(\pi z/L)$ in z over the cell length L in each cell, z=-L/2 to z=L/2. These curves allow us to make a reasonable choice of beta range to use for a group of cavities of a given fixed geometry.

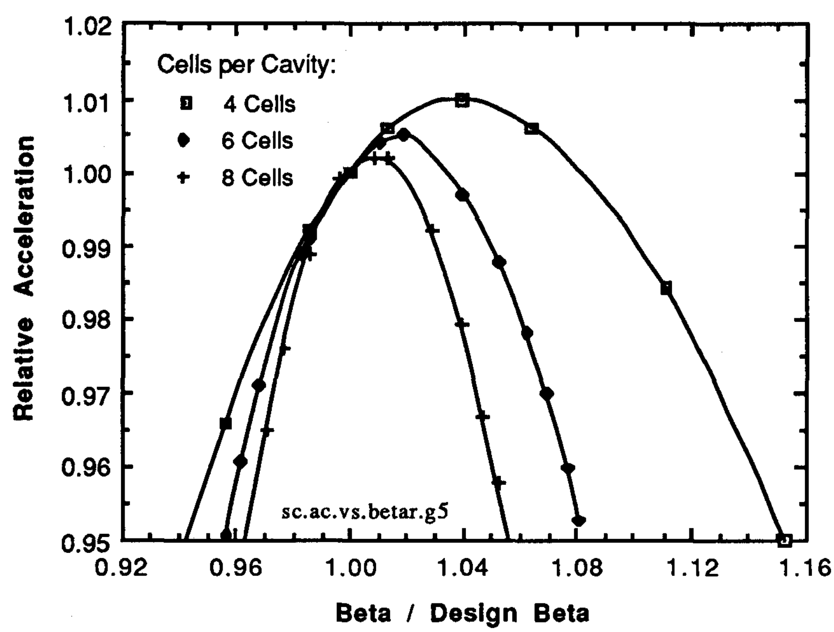

Fig. 3. Relative acceleration vs relative beta for 4, 6, and 8 cells per cavity.

Reference Linac Designs

Our goals for the linac design included:

Proton energy range:	0.1 to 2.0 GeV
Beam currents:	2.78 mA avg. for spallation source (90% ring injection efficiency) Up to 5 mA avg. in addition
Configuration:	Superconducting cavities Linac in groups of cavities with fixed geometry
Transverse focusing:	Quadrupole doublets
Fault tolerance:	Allow operation with one cavity down in each group Operation with reduced acceptance if one quad doublet down.

For a 5-MW spallation source, we need to accumulate 2.5 mA at 2.0 GeV. Thus, if the accumulator ring has 90% injection efficiency, we need to have the linac furnish 2.78 mA. In addition to this, the linac is to provide up to 5 mA average current for other uses. We wanted superconducting cavities for this accelerator, since the high accelerating gradients possible are needed in order to have the linac fit in the LAMPF tunnel. The length of cavities changes from group to group, and we envisioned increasing the spacing between focusing elements with increasing momentum along the machine. Under these circumstances, we found quadrupole doublets were easier to use than quadrupole singlets.

The design was subject to these additional constraints and assumptions:

RF frequency:	402.5 MHz	805 MHz
Maximum surface field E:	15 MV/m	17 MV/m
Maximum cells per cavity:	5	7
Cavity spacings, no doublet:	70 cm	59 cm
Cavity spacings at doublet:	320 cm	300 cm
Max. doublet spacing:	14 $\beta\gamma$ m	14 $\beta\gamma$ m
Max. doublet separation:	12 cav.	18 cav.
Max. power through couplers:	200 kW peak	100 kW peak
Synchronous phase:	-30 deg	
Min. long. acceptance:	40 pi-mm-mrad nor.	
Linac length:	730 m or less	
Cryogenic load, cav. surface:	$Q_0 = 5 \times 10^9$	
Ambient power leaks:	3 W/m of cryostat length 1 W per transition to room temp. 2.4 additional W per cavity.	

Maximum electric fields on the cavity surface of 17 or 18 MV/m correspond to accelerating gradients of 8.5 or 9 MV/m for high beta cavities. This is only slightly higher than what has been achieved at CEBAF, where their cavities have produced an average accelerating gradient of 8 MV/m.

We assume that the series of cavities between doublets will be housed in a single cryostat. Within the cryostat, the 59-cm spacing between 805-MHz cavities allows space for power and higher-order mode couplers, flanges, and bellows. The 300-cm spacing between 805-MHz cavities where there is a doublet allows room for transitions to room temperature, the doublet, and space for beam diagnostics and vacuum connections. The maximum doublet spacing is specified in order that the performance of the transverse focusing system not be unduly sensitive to errors in the quad gradients. The maximum doublet separation in number of cavities limits the length of cryostats, as well as further limiting the doublet separation in length.

One further assumption is necessary to proceed with the design, namely, the time structure of the beam. We assume the beam current from the linac is divided between two beam lines at 2.0 GeV, Line 1 supplying the accumulator ring for the 5-MW spallation neutron source, and Line 2 supplying beam used for other purposes. We assume the beam in the linac comes in macropulses with a duty factor of up to 40.3%, of which 14.4% goes to the accumulator ring, as shown in Table I. The independent parameters are indicated by asterisks. In addition to the slow pulsed structure of the beam, there is a fast chopping of the current (to allow a few-hundred-ns gap in the ring current for extraction). The chopping pattern is fast compared with the response time of the rf system, and we therefore talk about effective peak current or effective peak power, which are the current or power averaged over the chopping period.

The results from Table I may be applied either for 402.5 or 805 MHz. In the following, we will be talking about the 805-MHz case, unless otherwise noted.

Table I
Beam Current Parameters

Average Current, Line 1 (mA) (to ring)	*	2.778
Average Current, Line 2 (mA) (other)	*	5.000
Duty Factor, Line 1 (%)	*	14.4
Duty Factor, Line 2 (%)		25.92
Total Duty Factor, Beam (%)		40.32
Chop Fraction (%)	*	65.0
Total Average Current (mA)		7.778
Peak Current, Micropulse (mA)		29.68
Eff. Peak Current, Chopped (mA)		19.29

The procedure we used to design the linac is as follows:

(1) We begin by assuming the first group of cavities has 10 cavities of 7 cells each.

(2) We may then estimate the energy gain over the first or current group. This is done by trial. We guess the energy gain and see if it corresponds to the expected number of cavities as follows:

(a) We find the average energy for the group from the initial and final energy.

(b) We find the relativistic beta corresponding to the average energy.

(c) We calculate the maximum permissible E_0T using Eq. (1) and the specified peak surface field E_{max}.

(d) We find the actual E_0T to be used by multiplying the maximum permissible value by a factor not more than (n-1)/n, where n is the number of cavities in the group. This derates E_0T such that one cavity in the group can be down, and there is still margin to increase the field of other cavities in the group to compensate.

(e) We find the approximate energy gain per cavity using E_0T from step (d) and the length of the cavity and the assumed synchronous phase. (This does not include the effect given by Eq. (4).)

(f) We divide the assumed energy range for the group by the gain from step (e) to find the number of cavities in the group.

If the number of cavities we find is not what we expected, we adjust the final energy of the energy range and try again from step (a).

(3) For the current group of identical cavities, we want the energy range for the group to be such that the ratio of final to initial relativistic velocity beta is not more than a specified value. For example, if we have seven cells per cavity, we deduce from Fig. 3 that we can be within 98% of maximum acceleration if the ratio of final to initial beta is 1.07. If the ratio of final to initial beta is much less than our specified value, we may increase the energy range and the number of cavities in the current group. If the ratio of final to initial beta exceeds our specified value, we choose a smaller energy range or a fewer number of cells per cavity for the current group. For these special cases, we then try again, beginning at step (2).

(4) We check that there are at least 10 cavities in the group, or at least the number n we used in step (2)(d). If we get less than this number of cavities in the group, we need to lower the number of cells per cavity and try again, beginning at step (2).

(5) We check that the effective peak power supplied by the main power coupler is not greater than 100 kW. If it exceeds this, we need to reduce the number of cells per cavity and try again, beginning at step (2). Alternatively, we can reduce the effective peak current by increasing the beam duty factor. If we do this, we have to restart (or at least recheck) our design from the beginning.

(6) When all of the above is satisfactory for the current group, we go on to the next group, make a guess as to how many cavities are to be in this new group, and continue through steps (2) - (6) as needed.

(7) When we have completed all the groups for the whole linac, we check to see if the total length is satisfactory. If it is too long, we might see if it is reasonable to increase the peak surface field or decrease the cavity spacings, and begin the design again.

We have used a spreadsheet to help implement this procedure, and we have been able to generate a preliminary linac design very quickly. We then go on to use more sophisticated computer codes to work out further details of the design and check its performance.

An approximate linac design for 805-MHz cavities is given in Table II. The table shows the range of energy and beta for each group of cavities in the linac, the design beta, the number of cavities per quad doublet, the number of cells per cavity, and the number of cavities in each group. It also gives the derating fraction, the amount E_0T is reduced from its maximum permissible value in normal operation, and the accelerating gradient that we may use such as to keep the effective peak coupler power less than 100 kW.

We next used the design beta and E_0T data from Table II to generate a more detailed linac design using the LIND3 computer code. We verified that 454 cavities accelerated the beam to slightly over 2.0 GeV in 720.6 m when the cavity spacing at the doublets was 3.00 m. We used the SIMALAC code to verify that the linac was capable of accepting beams with horizontal and vertical normalized emittances of 40 pi-mm-mrad, which allowed space for the halo as well as the core of the beam. With large-bore superconducting cavities accelerating and transmitting large beams, we expected that space charge would produce little emittance growth, and our SIMALAC calculations have confirmed that this is true.

Table II

805-MHz Approximate Linac Design

Win, Wout (MeV)	β_f/β_i	β_d	Cavs. /QD	Cells /cav.	Cavs. /group	De-rate	E_0T (MV/m)	Coup. P (kW)
100.00, 116.43	1.067	0.443	3	7	10	0.90	3.2878	31.70
116.43, 134.92	1.063	0.471	3	7	10	0.90	3.4724	35.65
134.92, 157.84	1.065	0.502	4	7	11	0.90	3.6802	40.20
157.84, 186.25	1.066	0.535	4	7	12	0.90	3.9225	45.67
186.25, 221.40	1.066	0.570	5	7	13	0.90	4.2014	52.16
221.40, 264.78	1.065	0.608	5	7	14	0.90	4.5167	59.76
264.78, 319.27	1.064	0.647	6	7	15	0.92	4.9768	70.10
319.27, 391.10	1.064	0.688	6	7	17	0.93	5.4384	81.51
391.10, 507.85	1.074	0.737	8	6	27	0.95	6.0649	83.40
507.85, 745.50	1.091	0.800	11	5	54	0.96	6.8199	84.89
745.50, 1099.25	1.069	0.864	17	4	84	0.97	7.5604	81.24
1099.25, 2008.66	1.068	0.926	18	4	187	0.97	8.1380	93.81

Total length: 729.79 m (assumes cavity spacing for doublets is 3.59 m)
Total number of cavities: 454

Calculated Performance

From our approximate design data, we estimated the peak magnetic field on the surface of the cavity, the expected shunt impedance-to-Q ratio from Eq. (3), and the expected load on the cryogenic system. These data are given in Table III. The power-per-cavity and ambient-power values assume the rf duty factor was 43.3% (3% more than the beam duty factor to allow for the rf rise time), the cavity Q was 5 x 10^9, each cavity loaded the cryogenic system by an additional 2.4 W to represent the cooling of the rf and HOM couplers, etc., and the cryostats had a further ambient power load of 3 W/m and 1 W per transition to room temperature, as specified in the list of constraints and assumptions given previously.

Table III
805-MHz Approximate Linac Design - Cryogenics, Etc.

Beta	H_{max} (A/m)	Cav.L. (m)	ZT^2/Q (ohms/m)	P/Cav. (W)	Amb.P (W)	# Cavs.	Cryo.P (W)
0.44286	28981	0.5772	56.92	7.15	4.17	10	113.1
0.47148	28617	0.6145	70.76	6.93	4.28	10	112.2
0.50170	28261	0.6539	84.78	6.92	4.23	11	122.7
0.53469	27913	0.6969	99.42	7.07	4.36	12	137.2
0.57016	27604	0.7432	114.35	7.37	4.40	13	153.0
0.60762	27372	0.7920	129.23	7.81	4.55	14	173.1
0.64682	27867	0.8431	143.82	8.69	4.63	15	199.7
0.68833	28244	0.8972	158.17	9.66	4.79	17	245.8
0.73680	29266	0.8232	173.50	9.96	4.49	27	390.1
0.80033	30803	0.7451	191.26	10.25	4.19	54	779.4
0.86354	33299	0.6432	206.31	10.12	3.82	84	1170.4
0.92643	36507	0.6900	218.69	11.45	3.95	187	2879.7
							6476.3

We have also calculated the expected beam dynamics performance of the linac, using our more detailed design and the SIMALAC particle-tracking code. We have calculated the longitudinal acceptance of the linac in normal operation and when certain cavities were shut down. The performance of the linac is more sensitive to one cavity being down when the crippled cavity is near the start of the linac than when it is farther downstream. At the start of the linac, there are three cavities per quad doublet. The spacing between cavities is larger when there is a doublet than when there is not. The worst case of a single cavity being down is thus when the third cavity is down, since this has the effect of lengthening the already larger spacing at the first doublet. The acceptances for normal operation, for cavity 2 only being down, and for cavity 3 only being down, are shown in Fig. 4. For such faults, the longitudinal acceptance is only slightly reduced from that for normal operation. The acceptance for normal operation and for cavities 225 and 226 both being down is shown in Fig. 5. There is no distinguishable change in the acceptance at the accuracy level of these calculations. When simulating these faults, we increased the accelerating gradient in the other cavities of the group, making the linac final energy as it should be in normal operation.

We also checked the transverse acceptances to see if they were affected by one or two cavities being down as specified above. We found slight changes when cavity 2 or cavity 3 was down, but the acceptance area still included the normal 40-pi-mm-mrad normalized emittance beam. These results are shown in Figs. 6 and 7. When we calculated the acceptance for cavities 225 and 226 only being down, the transverse acceptances were indistinguishable from those for normal operation.

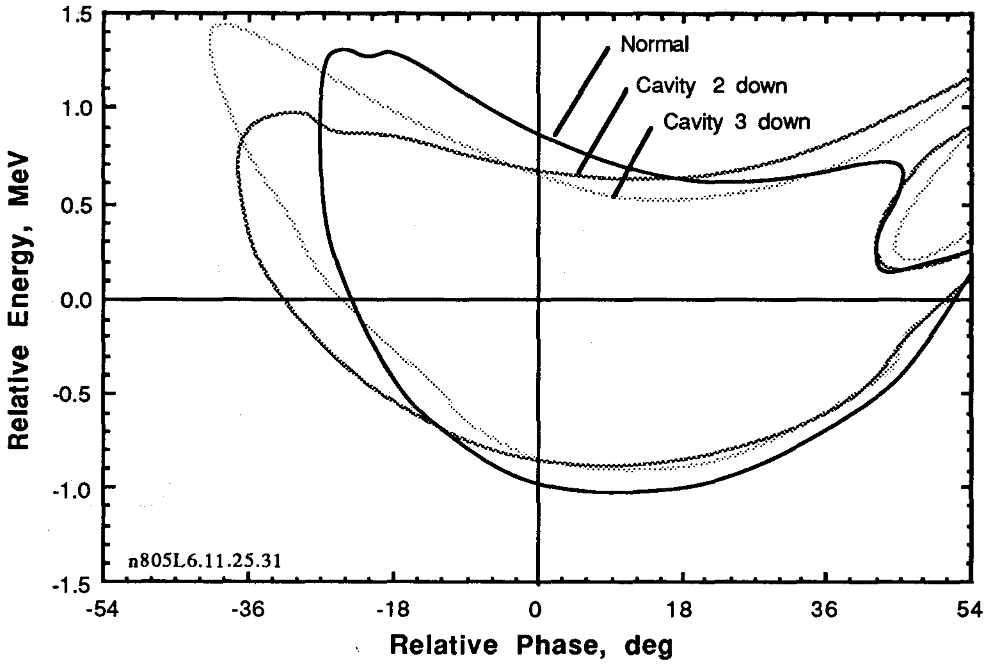

Fig. 4. Linac longitudinal acceptance for normal operation, and for cavity #2 or cavity #3 only being shut down.

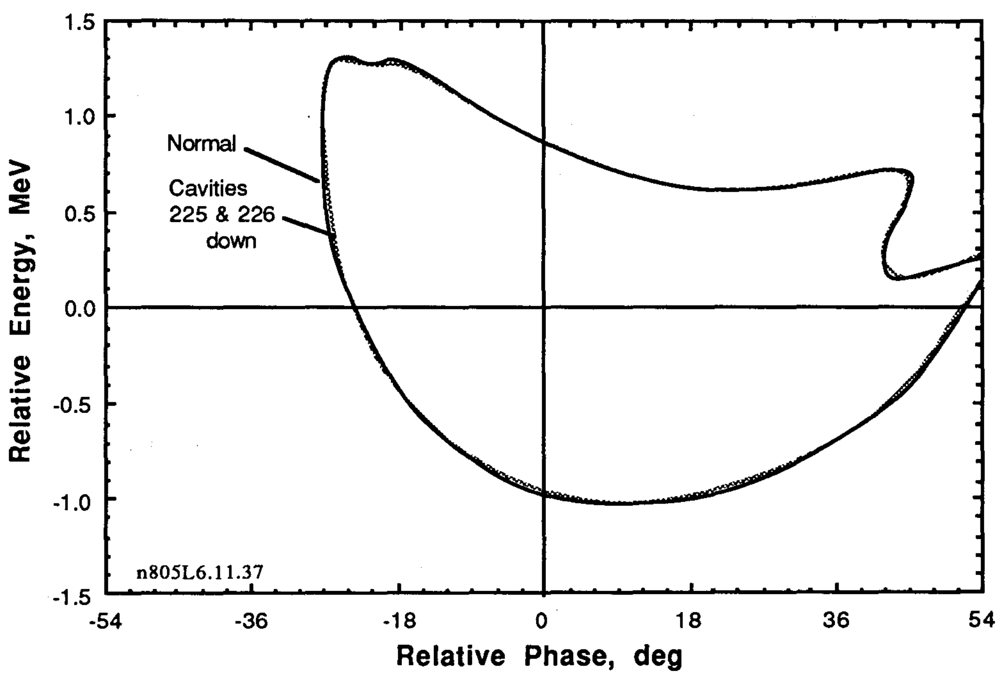

Fig. 5. Linac longitudinal acceptance for normal operation, and for cavities #225 and 226 only being shut down.

We have also calculated the transverse acceptance for a few cases in which one quadrupole doublet was down. If no readjustments are made to the other doublet strengths, the acceptance is only about 25% of that for normal operation. For normal operation, we used a tune with about 85 deg phase

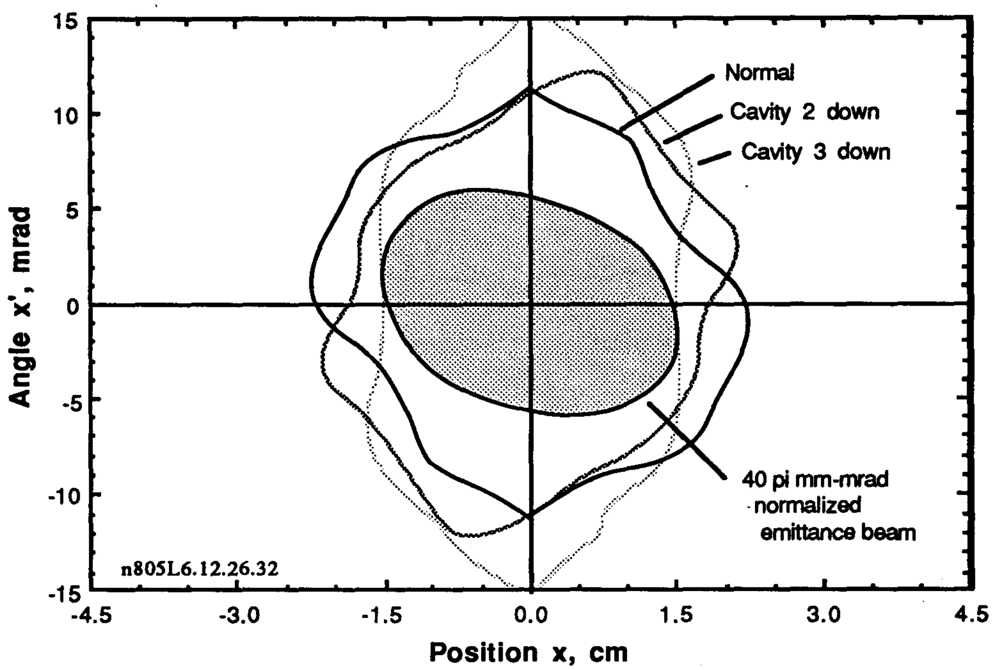

Fig. 6. Horizontal transverse acceptance for normal operation, and for cavity #2 or cavity #3 only being shut down.

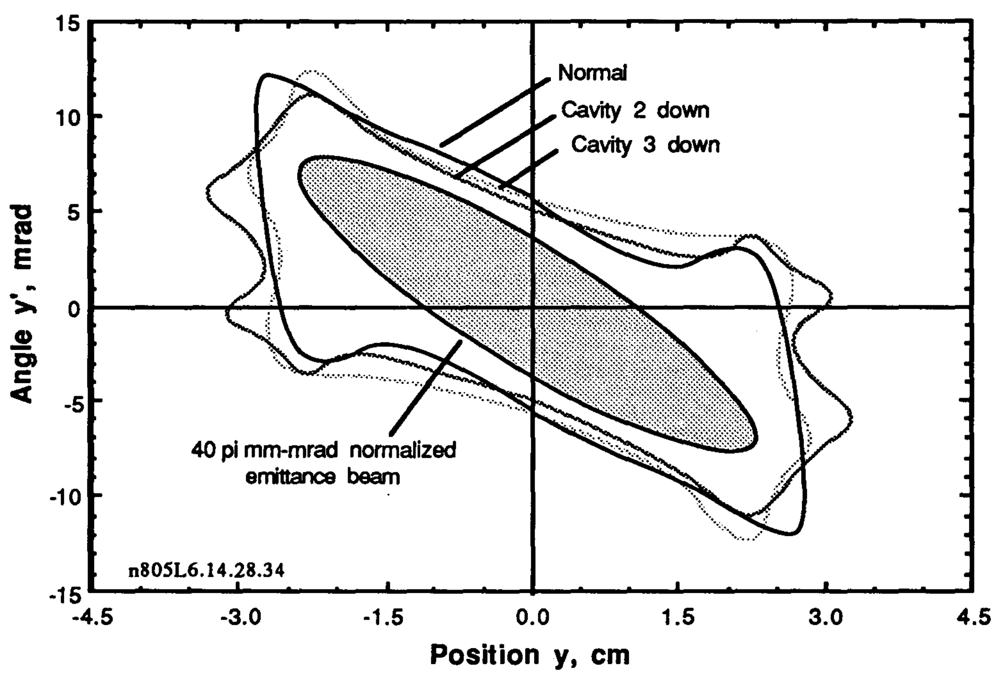

Fig. 7. Vertical transverse acceptance for normal operation, and for cavity #2 or cavity #3 only being shut down.

advance per focusing period. If we go to a tune with about 55 deg, the acceptance with all quads operating is about 35 pi-mm-mrad normalized. With this tune, but with the third quad only down, readjustments of the nearby doublets help, and the best acceptance for the readjustments that we have tried is about 33% of that for normal operation.

Conclusions

The 805-MHz linac that we have proposed could accelerate protons from 0.1 to 2.0 GeV in less than 730 m for a peak surface field in the cavities of 17 MV/m. Our design uses a total of 454 cavities arranged in twelve groups, identical cavities being used within each group. For an effective peak beam current of 19.29 mA and a beam duty factor of 40.3%, we were able to keep the effective peak power fed by each rf coupler to less than 100 kW for all of the cavities. We needed 14.4% duty factor for the part of the beam going to the spallation neutron source, and 25.9% duty factor for the part going to other uses, when 5 MW is supplied to the neutron source and a full additional 10 MW of beam is supplied for the other uses.

We found space charge to have a negligible effect on emittance growth for the transversely-large beams employed in this design.

In the design, we derated the accelerating gradient in each of the twelve groups of cavities such that one cavity per group could be inoperable, and the gradient in the remaining cavities in the group could be increased to compensate. The longitudinal and transverse acceptances of the linac were not significantly degraded under such fault conditions.

We are also in the process of developing a corresponding 402.5-MHz linac. The 402.5-MHz design has larger cavities, but might be operated at 4.2 deg K, instead of the 2 deg K required by the 805-MHz design. The 402.5-MHz design has the additional advantage that the longitudinal acceptance is larger.

We estimated the power that the cryogenic system will need to extract to be 6.5 kW for the 805-MHz design, as opposed to 20.2 kW for the 402.5-MHz design. Even with helium at 4.2 deg K being used for the 402.5-MHz design and 2 deg K for the 805-MHz one, the power savings from using 805 MHz in place of 402.5 MHz might be substantial. However, the technology of large 2 deg K systems is not as well developed as for large 4.2 deg K systems.

Further work needs to be done to establish the design of the portion of the linac that accelerates the protons to 0.1 GeV, to confirm the performance of the twelve cavity types needed above 0.1 GeV for the 805-MHz design, to complete the alternative 402.5-MHz design, and to properly match the beam from the upstream to the downstream part of the linac.

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