FERMILAB-LU-158

Transition Section Design Rationale and New Parameters
LU – 158

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Abstract

The detailed design of the transition section has been critically reviewed to permit freezing the length requirement so that rf penetrations for the entire linac can be located and the space available to the 400 MeV line design can be established. Decisions about power sources for the buncher cavities, nominal operating conditions, and access to tank 5, made since the writeup in Revision 4A of the Conceptual Design, result in the new parameters reported here. The underlying concepts of the longitudinal matching are discussed. An apparent error in the length of the space freed by removing tanks 6 – 9 is noted. Corrected versions of various parameter tables and summary tables affected by the new design are collected in an appendix.

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Introduction

The fundamental design of the transition section is a buncher cavity followed by a drift to reduce the width of the 201 MHz bunches from $\pm 20°$ of 805 MHz phase to about $\pm 10°$. The section must also have at least four quads to match the transverse phase space parameters α_x, β_x, α_y, and β_y. However, the properties of the 116.5 MeV beam leaving tank 5 have not been directly measured; they have been inferred from simulations connecting them to measurements made elsewhere in the linac. The simulations have also been compared to expectations based on design values. The flexibility to adjust for unexpected longitudinal phase space properties is provided by including a smaller buncher cavity halfway along the bunching drift. This note will justify the choice of the strength and spacing of the transition section components by results of first order calculations including space charge. Nominal parameters and the range of adjustment for differences from nominal are given. Where design criteria have changed or been refined since the last version of the conceptual design[1] there is at least some discussion of the need for the changes. The changes affect the linac itself very little; however, various parameter and summary tables are affected by the new length of the transition section. All of the tables maintained by the author which have any resulting changes are attached as an appendix.

Matching Requirements

The first and crucial parameter to be established is the length required for the bunching process. This length and the buncher gradient are determined from the bunch width and longitudinal emittance of the 116.5 MeV beam. The longitudinal emittance has been calculated from the bunch width and momentum spread measured at 200 MeV. Ideally the match between the old and new machines is made by obtaining in each the same value for the longitudinal beam envelope width function β_l. This function is analogous to the Courant-Snyder functions β_x and β_y for the transverse envelopes:

$$\beta_l = (\Delta t)^2/\varepsilon_l \ , \tag{1}$$

where ε_l is the longitudinal emittance in eVs and Δt is the bunchwidth in seconds. Thus, β_l has units s/eV. The longitudinal emittance is needed to determine β_l from the bunch width, but if β_l is correctly matched, the transition section will work for any emittance small enough to keep the bunch width within the approximately linear region of the buncher potential.

One can readily calculate β_l in the limit of zero beam current. The linearized equations of motion for the longitudinal coordinates are

$$\begin{aligned} \frac{d\tau}{ds} &= \frac{1}{c\, m_o c^2\, (\beta\gamma)^3}\epsilon \stackrel{\text{def}}{=} a\epsilon \\ \frac{d\epsilon}{ds} &= -eE_oT \sin\varphi_s\, \omega\tau \stackrel{\text{def}}{=} -b\tau \ , \end{aligned} \tag{2}$$

where $\tau = \Delta s/\beta c$ and $\epsilon = E - E_s$. These are Hamilton's equations for a Hamiltonian

$$H = \frac{a}{2}\epsilon^2 + \frac{b}{2}\tau^2 \quad . \tag{3}$$

The Hamiltonian is a constant of motion, so with $A^2 = 2H/a$ and $B^2 = 2H/b$ the trajectory

$$\frac{\epsilon^2}{A^2} + \frac{\tau^2}{B^2} = 1 \tag{4}$$

is fixed. Defining the longitudinal β for $\alpha_l = 0$ by

$$\begin{aligned} \tau_{\max} &= \sqrt{\beta_l \varepsilon_l} \\ \epsilon_{\max} &= \sqrt{\varepsilon_l/\beta_l} \end{aligned} \tag{5}$$

one finds

$$\frac{\tau_{\max}}{\epsilon_{\max}} = \beta_l = \frac{B}{A} = \sqrt{\frac{a}{b}} \quad . \tag{6}$$

Thus,

$$\beta_l = [c\, m_o c^2\, (\beta\gamma)^3 \omega e E_o T \sin\varphi_s]^{-\frac{1}{2}} \quad . \tag{7}$$

The frequency in tank 5 is 201.25 MHz, the nominal gradient is 2.56 MeV/m, the the 116.5 MeV transit time factor is 0.69, and the synchronous phase is $-32°$. Therefore,

$$\begin{aligned} \beta_l &= (3.00 \cdot 10^8 \frac{\mathrm{m}}{\mathrm{s}} (.514)^3 938\,\mathrm{MeV} \times 2.56 \frac{\mathrm{MeV}}{\mathrm{m}} \times 0.69 \times 2\pi \times 2.01 \cdot 10^8 \mathrm{s}^{-1} \times .530)^{-\frac{1}{2}} \\ &= 1.49 \cdot 10^{-10} \frac{\mathrm{s}}{\mathrm{MeV}} \end{aligned}$$

The phase coordinates are more conventionally taken as a phase angle interval and some reasonable multiple of eV:

$$\beta_\varphi = \beta_l \left[\frac{\mathrm{s}}{\mathrm{MeV}}\right] \times 360[\mathrm{deg}] f[\mathrm{s}^{-1}] = 0.0108 \left[\frac{\mathrm{deg}}{\mathrm{keV}}\right] \quad .$$

To get the β in the first module of the new linac one can scale these results by the square root of $f \times E_o T$:

$$\beta_{805}^{-2} = 4(5.73/1.77)\beta_{201}^{-2}$$

so that at 805 MHz

$$\begin{aligned} \beta_l &= 4.13 \cdot 10^{-11} \left[\frac{\mathrm{s}}{\mathrm{MeV}}\right] \\ \beta_\varphi &= .0120 \left[\frac{\mathrm{deg}}{\mathrm{keV}}\right] \quad . \end{aligned}$$

Note that the module 1 gradient has been scaled down by the "rf filling factor" 16/19 to account for the presence of the inter-section drifts.

Table I: Matched β_φ in Tank 5 and Module 1 *vs.* Beam Current

I_{beam} [mA]	Tank 5 β_φ [deg/keV]	Module 1 β_φ [deg/keV]
0	0.0108	0.0118
35	0.0127	0.0122
50	0.0135	0.0123

The results for $I_{beam} = 0$ matching calculated by TRACE-3D[2] are $\beta_\varphi|_{201} = 1.08 \cdot 10^{-2}$ and $\beta_\varphi|_{805} = 1.18 \cdot 10^{-2}$ as shown in in Figs. 1 and 2. The effect of space charge on β_φ will be greater at 201 MHz because of the smaller rf gradient. TRACE-3D results for current from 0 to 50 mA are given in Table I. The comparison of the TRACE and the analytic results at $I_{beam} = 0$ is a useful check that TRACE has been used correctly. This is an imported program on which the upgrade relies heavily for calculations of matching including space charge. The results can also be checked with the particle tracking code DDYN, but the gap transformations in that code have in fact been converted to those used in TRACE-3D.[3]

Practically speaking, beam current has no effect on the matched longitudinal β in the new linac, but it does affect the transverse β's and betatron phase advance because the transverse focusing is weaker in the new linac than in the drift tube linac. However, the effect on β_φ in the drift tube linac is of practical significance. Because the typical operating level for the present linac is in the range 30 – 35 mA, it has been decided to take 35 mA as the design point for the longitudinal match even though the design specifications for the new linac set 50 mA as the design current. There need to be adjustable elements in the transition section to provide for the range of uncertainties in possible operating conditions. Operation at 50 mA is one of the possible conditions, but it is intended to represent an upper bound for the design. Therefore, it is reasonable to take the present level as more characteristic of future operation, especially because it provides by few-turn injection all the intensity for which use is now foreseen. The β_φ^{out} was found initially by calculating the match in an acceleration-free system with the same rf focusing as section 1 of module 1. A small improvement to the global match in the 400 MeV linac was obtained by empirical adjustment resulting in a $\beta_\varphi^{out} = 0.0131$ deg/keV.

New Parameters

A tentative choice of the power source for the buncher cavities is a "catalog item" klystron designed for 50 kW cw TV service. It is available with a guarantee for operation at 200 kW pulsed. Setting the available power at this level and leaving some reserve for matching off-nominal beam conditions leads to a longer buncher cavity than that described in the Conceptual Design Report. The design that is presented below is optimized around a 16-cell

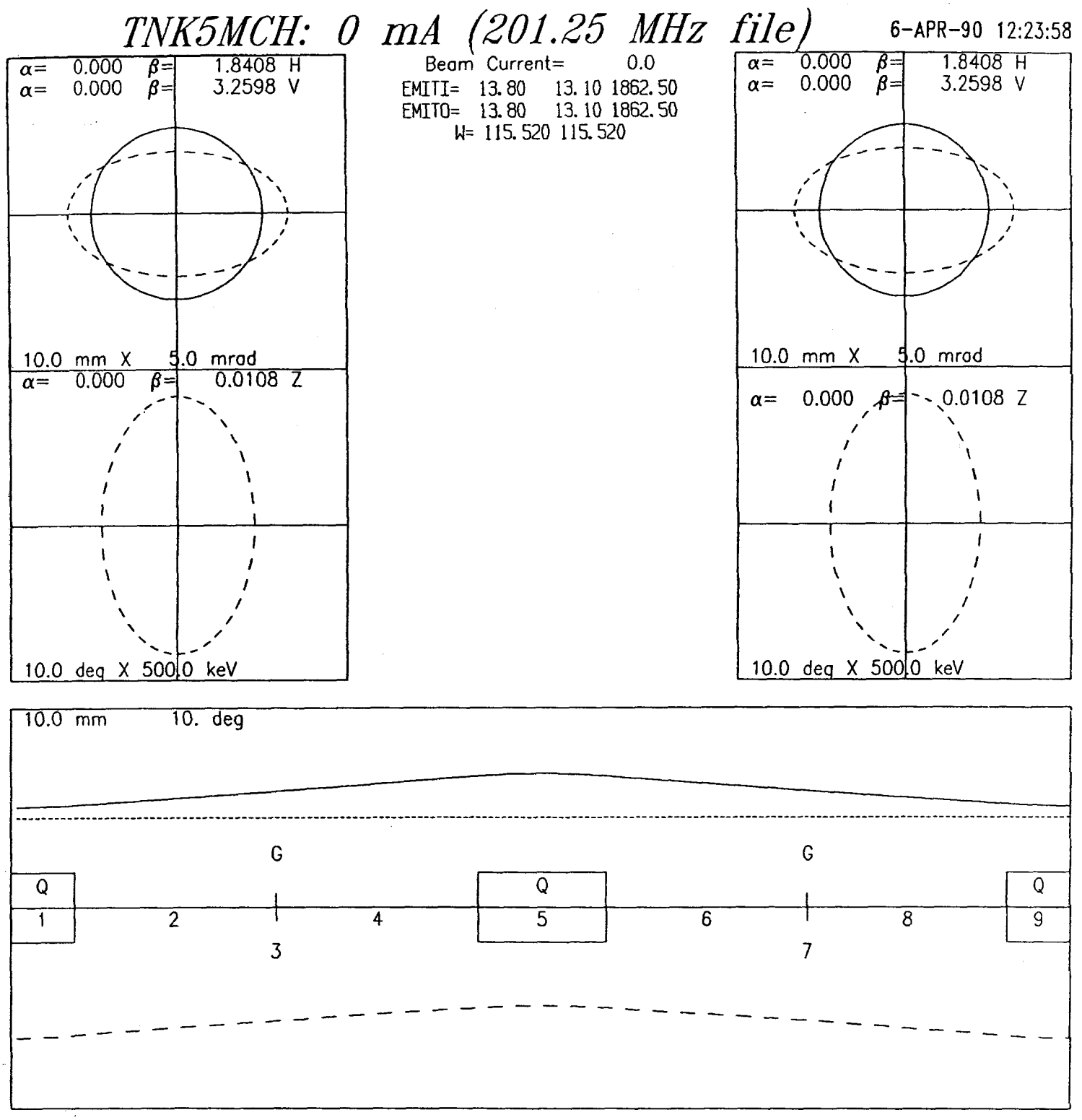

Figure 1: Matching conditions at the end of Tank 5 calculated by TRACE-3D for an equivalent non-accelerating system

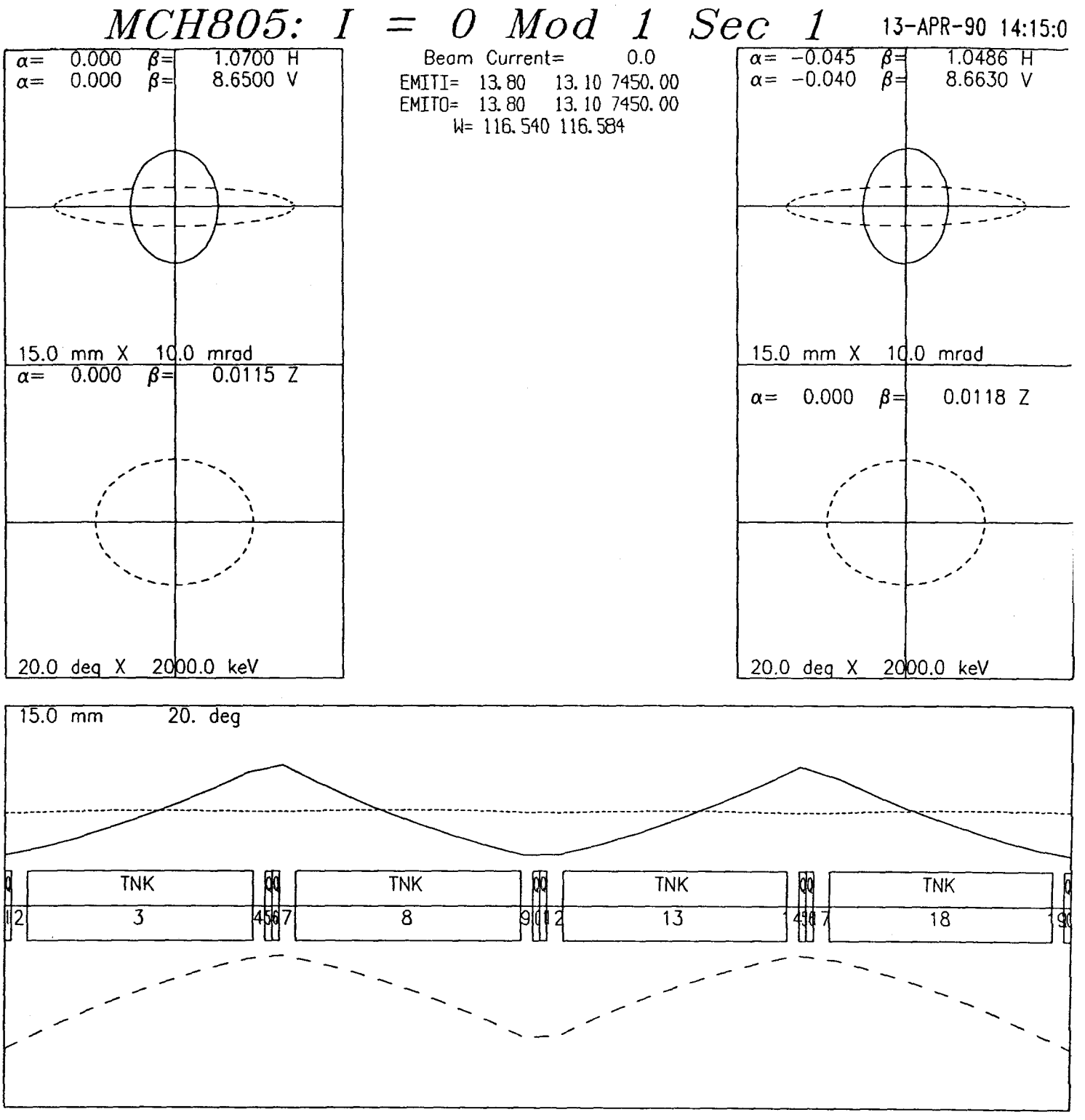

Figure 2: Matching conditions at the beginning of Module 1 calculated by TRACE-3D for an equivalent non-accelerating system

buncher. This is long enough to require a quad between tank 5 and the buncher to control the transverse envelope. Therefore, the new transition section design uses two of the drift tube quads and three upgrade quads instead of the three and two respectively used in the Conceptual Design version. The gradients and spacings of the components are given in Table II. The total length exceeds that of the previous version by only 37.7 cm. Fortunately, the gradients for the drift tube quads are lower than before, in fact nearly the same as in current operation. Because the last three tank 5 quads have independent power supplies, there is a sixth degree of freedom in the transverse match for reserve capability to adjust to unexpected beam conditions. Figure 3 shows the beam envelopes and phase space elipses from the last three drift tube quads through the first accelerating section of module 1. The bunch width is the dotted curve; the vertical envelope is the dashed curve. The layout of the rf and quads is is indicated along the axis of the envelope plot.

Figures 4, 5, and 6 plot the range of buncher 1 and buncher 2 gradients to match a range of $\alpha_\varphi^{\rm in}$, $\beta_\varphi^{\rm in}$, and $\beta_\varphi^{\rm out}$ respectively, each varied with all other parameters nominal. The limits of the gradient scales on the plots are about the operating limits of the cavities powered by a 200 kW source. The effective shunt impedance for the optimized SC structure at 116 MeV should be 36 MΩ/m. Thus, the maximum effective gradient is

$$(E_oT)_{\rm max} = \sqrt{\frac{P_{\rm max}ZT^2}{L}} = \sqrt{\frac{0.2 \times 36}{1.361}} = 2.3 \text{ MV/m} \ .$$

The multipactoring limit on the minimum gradient is expected to be below 1 MV/m on the basis of prototype II; it is quite likely there will be no problem at any significant excitation. Should input conditions correspond to a buncher 2 setting lower than 1 MV/m, the match obtained with gradient set to zero would be acceptable.

The tolerance of the transition section design to unexpected longitudinal phasespace of the input beam or output matching condition is characterized by Figs. 4 – 6. The most constrained input beam parameter appears to be α_φ with an acceptable range of $-0.5 \leq \alpha_\varphi \leq 0.4$. However, α_φ of greater magnitude is not common in PARMILA simulations of later tanks of the 200 MHz linac, and if it should occur, it could be improved by gradient and phase adjustments.

Tuning Tactics

For the transition section to work properly for a significant range of possible input conditions, it is necessary not only that there be a sufficient number of adjustable parameters with adequate range but also that there be the capability of making a sufficient number of independent beam measurements with accuracy adequate to establish that the desired match is obtained. The following discussion of the location of beam sensors demonstrates an approach to establishing practical adjustment; it does not include step-by-step procedures.

For transverse matching there are four groups of BPM, steering coils, and wire scanner each close to one of the four 8.6 cm quads. There is not enough space between tank 5 and buncher 1 to accommodate (or justify) two full groups there. Starting with calculated

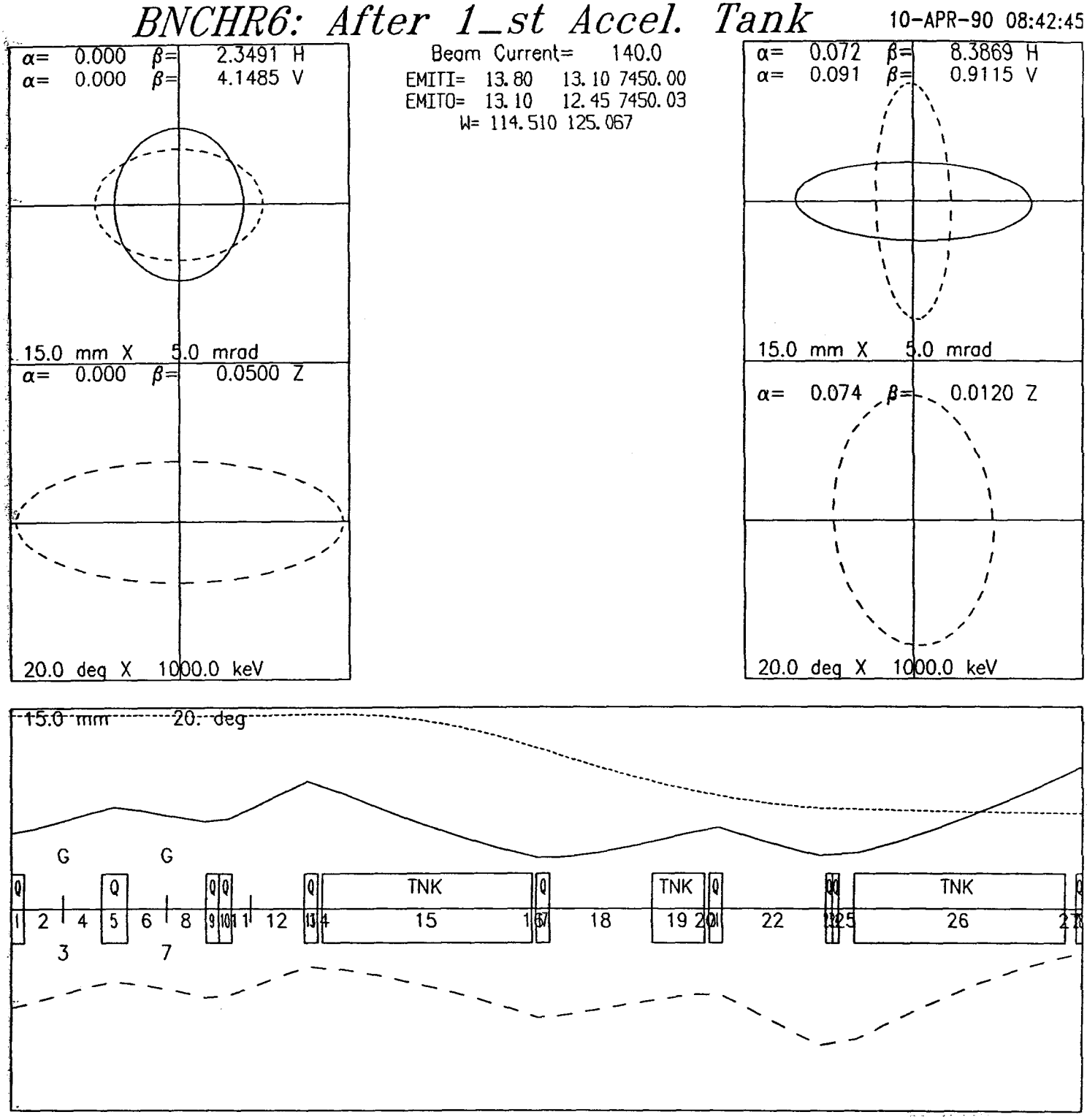

Figure 3: Phase space plots and beam envelopes from center of the third from last drift tube quad to the center of the quad between sections 1 and 2 of module 1. The bunch width is shown with a dotted curve, the horizontal envelope with a solid curve, and the vertical envelope with a dashed curve. The layout of quads and rf is indicated; only the longitdinal dimensions are to scale.

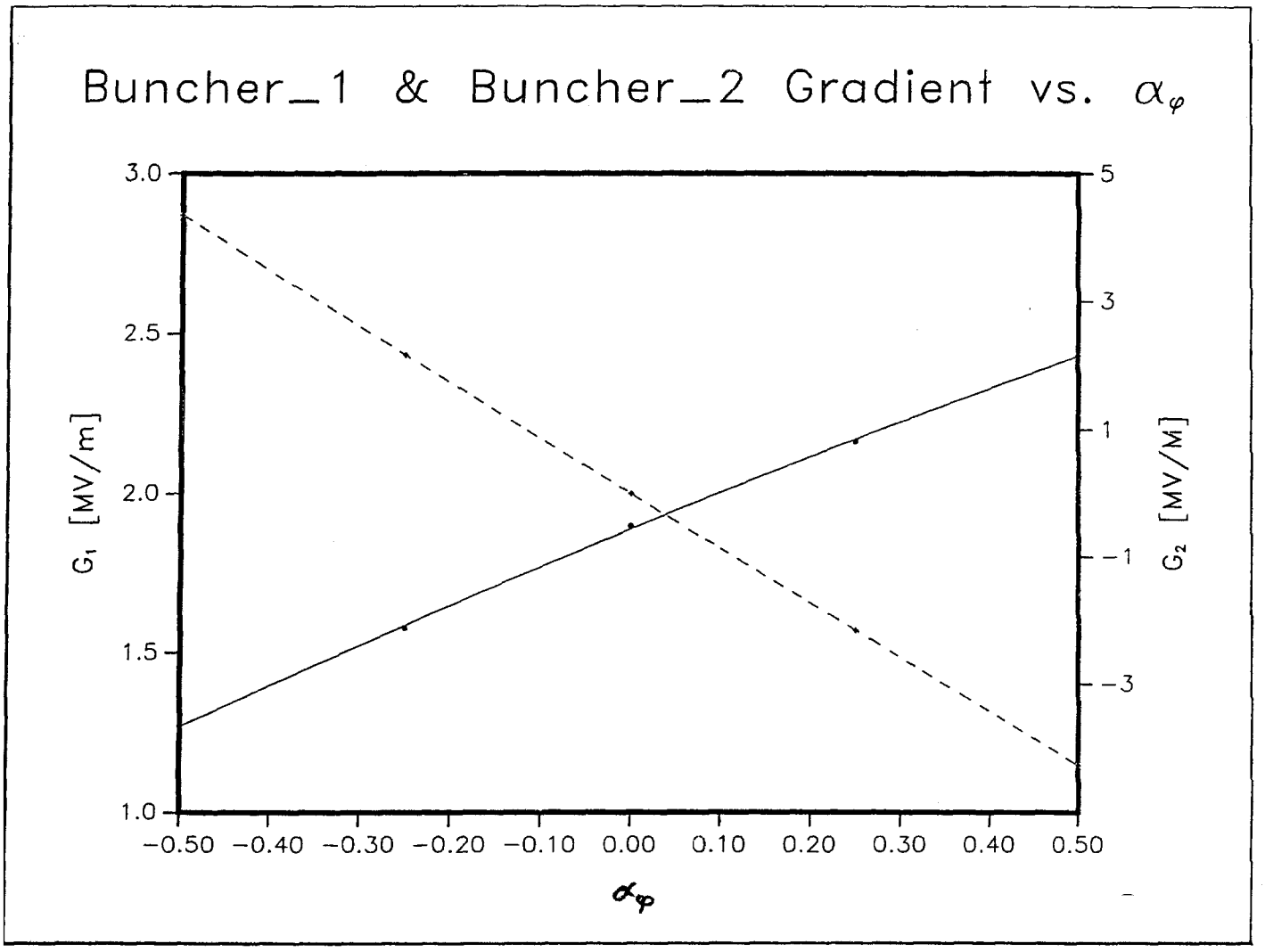

Figure 4: Values of the gradient for buncher$_1$ (left axis) and buncher$_2$ (right axis) *vs.* tilt of input ellipse α_φ^{in} with other beam parameters at nominal values

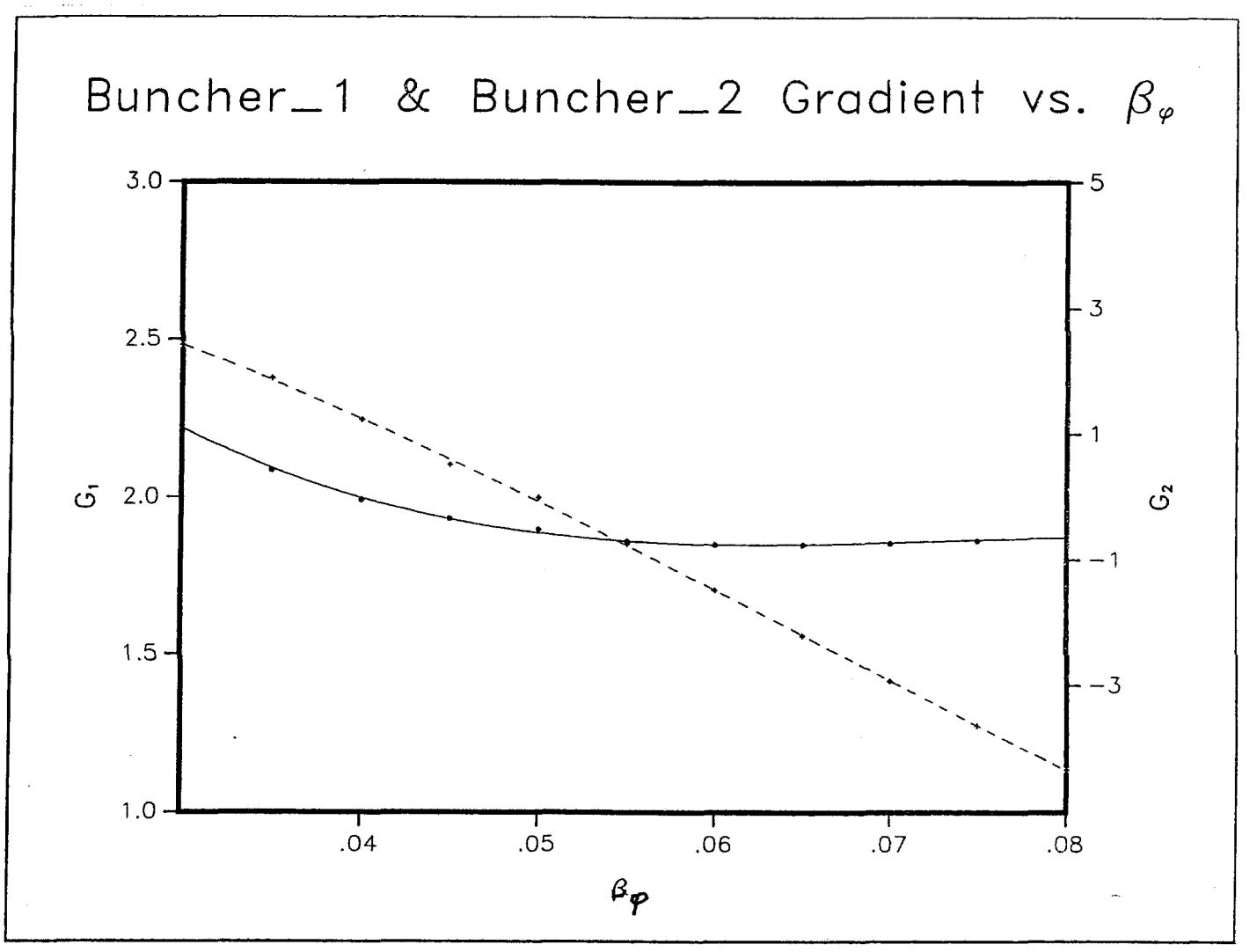

Figure 5: Values of the gradient for buncher$_1$ (left axis) and buncher$_2$ (right axis) *vs.* input bunch width parameter $\beta_\varphi^{\text{in}}$ with other beam parameters at nominal values

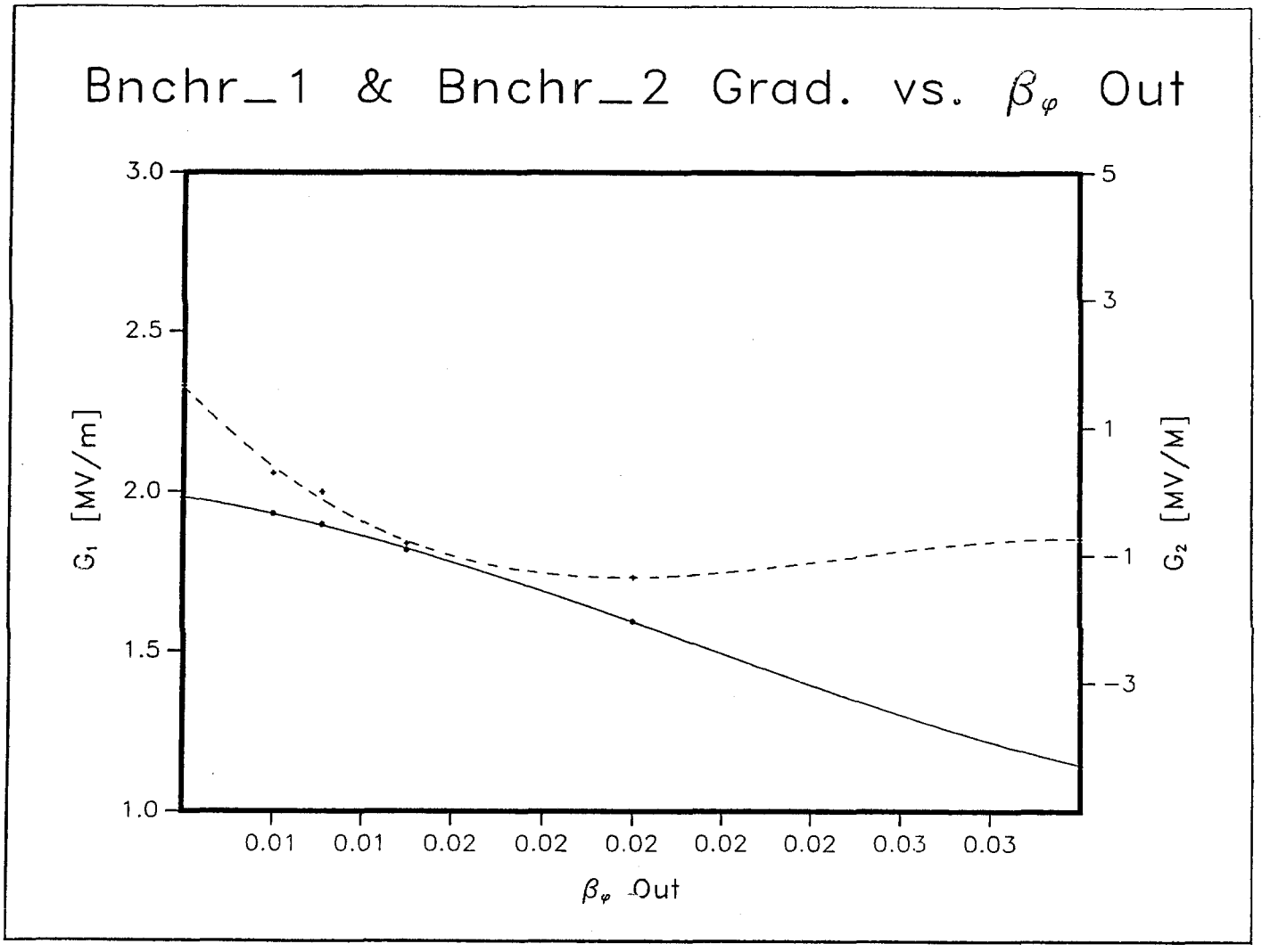

Figure 6: Values of the gradient for buncher$_1$ (left axis) and buncher$_2$ (right axis) *vs.* output bunch width parameter $\beta_\varphi^{\mathrm{out}}$ with other beam parameters at nominal values

nominal settings it should be possible to work downstream to make a series of waists spanning each of the wire locations and from this calculate back to put the waists in the design locations. Four wires are more than required in principle, but having a scanner near both the beginning and end of the transition section should facilitate the tuning and monitoring.

The basic procedure for longitudinal matching would be to adjust buncher 1 with buncher 2 off to find a minimum bunch width in the downstream bunch length monitor. If the bunch width measured at the upstream end is too far from nominal, it could be necessary to tune the 200 MHz linac to bring the input beam (including energy) into the transition section design window. With a bunch width minimum established at the downstream monitor it will be possible to obtain matched beam at the beginning of the first 805 MHz section by combining measurements at the central and downstream monitors with adjustments of the gradients of buncher 1 and buncher 2 inter-related by beam transport (*e.g.* TRACE-3D) calculations. In talking about buncher adjustment it was assumed that correct phasing had already been established by momentum *vs.* phase measurements made either with the 400 MeV spectrometer or time of flight along the un-excited linac.

Location of RF Penetrations

The location of the penetrations from the equipment gallery into the linac vault for the waveguides is given relative to the project z = 0 datum at the rf end plane of tank 5. For each accelerating module the location is the center of the central bridge coupler. For the transition section, locations at the downstream end of each buncher are given with an alternate midway between the two cavities to serve both if desired. See Table III.

Conclusion

The concept of the debuncher remains as defined in March '89,[?] but it has evolved somewhat, principally by

1. choice of 200 kW rf power source,
2. choice of 35 mA beam current as design center,
3. addition of 30 cm upstream of buncher 1 for tank 5 access.

In the crucial longitudinal dimension the result has been an increase of length from 3.623 m given in Revision 4A of the Conceptual Design to 4.000 m. The five-cell buncher 1 has been lengthened to sixteen cells to provide slightly higher bunching capability at lower power. The quad spacing has changed in a manner to reduce the required gradient on the drift tube quads to near ordinary operating levels, and greater flexibility for transverse matching has been obtained by introducing a new upgrade quad upstream of buncher 1.

In reviewing the the effect of design changes on the location of penetrations for rf, it was found that the design report value for the distance between the rf end planes of tanks 5 and 9 is in error by 19.5 cm, approximately, but not exactly, the 17.5 cm by which tank 5 was moved

downstream for the installation of NTF. Therefore, the available project length should be quoted as 66.805 m instead of the 67 m that appears in the Conceptual Design. The current figures come from the report on the linac given at the 1970 Proton Linac Conference at NAL[?] corrected by a 17.5 cm displacement for NTF. It would be tidier if the discrepancy were precisely the NTF displacement, but because the linac itself does not seem to be tied into the floor coordinates and the NTF shift is not all that well documented, the placement of penetrations can be determined with confidence only by a survey of the 200 MeV linac.

References

[1] *Fermilab Linac Upgrade Conceptual Design*, Revision 4A (November, 1989)

[2] K. R. Crandall,"TRACE-3D Documentation",Los Alamos report LA-11054-MS(August, 1987)

[3] L. W. Oleksiuk, priv. comm.

[4] J. A. MacLachlan, "400 MeV Upgrade for the Fermilab Linac", Fermilab-Conf-89/81(24 March 89), appearing in Proc. 1989 PAC at Chicago, 20 – 23 March 1989, p950

[5] D. E. Young,"Construction Progress and Initial Performance of the NAL 200 MeV Linear Accelerator", Proc. 1970 Proton Linear Accelerator Conf. held at Batavia 28 Sept. – 2 Oct. 1970

Table II: Transition Section Parameters

Element	Length [mm]	B′ [T/m]	E_oT [MV/m]	Proj. L. [m]	L_{sep} [mm]	D_Q [mm]	Devices
Q′/2	83.82	-10.183		0.08382			
flange	113.82			0.19764			
drift	351.62			0.54926			
Q	86.00	21.180		0.63526			
drift	30.00			0.66526			
$Bnchr_1$	1361.26		1.879	2.02652	665.26	73.00	Q′/2 B V C′ S W Q
drift	30.00			2.05652			
Q	86.00	-13.522		2.14252			
drift	679.08			2.82160			
$Bnchr_2$	340.31		-0.074	3.16192	795.08	722.08	Q B S W C′
drift	30.00			3.19192			
Q	86.00	20.910		3.27792			
drift	679.08			3.95700			
Q/2	43.00	-21.395		4.00000	838.08	765.08	Q B S W C′ T V B S Q/2

Note: New quad magnetic length arbitrarily set to 86.000 mm

Symbol	Device	Length [mm]
B	beam position monitor	30.0
C	current pickup	10.0
C′	bunch length monitor	300.0
Q	standard quadrupole	86.0
Q′	DTL quadrupole	167.6
S	steering trim magnet	60.0
T	toroid current monitor	31.0
V	vacuum gate valve	49.0
W	wire scanner	50.0

Note: Available for devices $3\beta\lambda/2 - 10$ cm.

Table III: z Location of RF Penetrations Relative to Tank 5

Name of device	Distance [m]
end bell	0.1976
Buncher 1 (d.s. end)	2.0265
Buncher 1 and 2	2.4241
Buncher 2 (d.s. end)	3.1619
Module 1	7.3426
Module 2	14.5450
Module 3	22.3987
Module 4	30.8231
Module 5	39.7479
Module 6	49.1137
Module 7	58.8681

Appendix: Table Updates

1. Design Report Table 2: Design Criteria and General Parameters
2. Design Report Table 3: Parameters of the 400 MeV Linac by Accelerating Section
3. Design Report Table 6: 116 MeV Matching Requirements
4. Design Report Table 7: Transition Section Parameters (Table II in text)
5. 400 MeV Linac - Summary Parameter Table (30 April 90)
6. 400 MeV Linac Upgrade - Principal Mechanical Dimensions (30 April 90)
7. 400 MeV Upgrade Linac - RF Power Budget (30 April 90)
8. 400 MeV Upgrade linac - Kinematic and Dynamic Quantities (30 April 90)
9. Numbers Derived from Energy and $\beta_{\mathbf{geom}}$

Table 2: Design Criteria and General Parameters for the 400 MeV SC Linac

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 ($\bar{I}_b$)	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 ($7 \times 4 \times 16$)	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

Design Report Table 3: Parameters of the 400 MeV Linac by Accelerating Section

Table 3: Parameters of the 400 MeV linac listed for each accelerating section

Module /Sect.	Grad. [MV/m]	KE_{out} [MeV]	L_{rf} [m]	L_{sep} [m]	P_{Cu} [MW]	P_{beam} [MW]	$\Delta\psi_{x,y}$ [deg]	$\Delta\psi_z$ [deg]
0					(Transition Section)			
1	2.23	116.5	1.3613	0.6653	0.13	0.00		
2	0.00	116.5	0.3403	0.7951	0.00	0.00		
			0.0000	0.8381				
			1.7016	2.2984	0.13	0.00		
			4.0000		0.13			
1	8.07							
1		125.1	1.3814	0.1418	1.75	0.43		
2		133.8	1.4215	0.2628	1.88	0.44	77	109
3		142.8	1.4606	0.2703	1.93	0.45		
4		152.1	1.4987	0.2775	1.91	0.46	78	106
			5.7621	0.9524	7.47	1.78		
			6.7145		9.25			
2	7.85							
1		161.2	1.5353	0.2846	1.72	0.46		
2		170.6	1.5704	0.2912	1.85	0.47	80	103
3		180.2	1.6047	0.2977	1.88	0.48		
4		190.0	1.6380	0.3041	1.88	0.49	80	101
			6.3484	1.1776	7.33	1.90		
			7.5260		9.23			
3	7.66							
1		199.7	1.6700	0.3102	1.70	0.48		
2		209.5	1.7009	0.3161	1.82	0.49	81	98
3		219.6	1.7309	0.3218	1.86	0.50		
4		229.8	1.7600	0.3273	1.85	0.51	81	96
			6.8618	1.2754	7.23	1.98		
			8.1372		9.21			
4	7.48							
1		239.9	1.7881	0.3327	1.68	0.51		
2		250.1	1.8151	0.3379	1.79	0.51	81	94
3		260.5	1.8414	0.3428	1.84	0.52		
4		271.1	1.8670	0.3477	1.83	0.53	80	92
			7.3116	1.3611	7.14	2.07		
			8.6728		9.21			
5	7.34							
1		281.5	1.8917	0.3524	1.67	0.52		
2		292.1	1.9155	0.3570	1.78	0.53	80	90
3		302.8	1.9387	0.3614	1.83	0.53		
4		313.6	1.9613	0.3657	1.81	0.54	79	89
			7.7072	1.4365	7.09	2.12		
			9.1436		9.21			
6	7.20							
1		324.4	1.9830	0.3698	1.66	0.54		
2		335.2	2.0039	0.3738	1.77	0.54	79	87
3		346.1	2.0244	0.3777	1.81	0.55		
4		357.1	2.0443	0.3815	1.79	0.55	78	85
			8.0555	1.5028	7.03	2.18		
			9.5583		9.21			
7	7.09							
1		368.1	2.0635	0.3852	1.65	0.55		
2		379.1	2.0821	0.3887	1.76	0.55	77	84
3		390.2	2.1002	0.3921	1.80	0.56		
4		401.5	2.1179	0.3955	1.78	0.56	76	82
			8.3637	1.5614	6.99	2.22		
			9.9251		9.21			
Grand			52.1119	11.5656	50.27	14.25		
Total			63.6775		64.66			

Table 6: 116 MeV Matching Requirements

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	cm
exit aperture	2.0	cm
116 MeV beam (nominal)		
β_x	2.18	m
β_y	3.84	m
β_φ @ 805 MHz	0.0500	deg/keV
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	1.07	m
β_y	8.65	m
β_φ @ 805 MHz	0.0131	deg/keV

400 MeV Linac - Summary Parameter Table

400 MeV Linac – Summary Parameter Table

30 April 1990

Module /Sect.	Grad. [MV/m]	KE_{out} [MeV]	L_{rf} [m]	L_{sep} [m]	Devices (upstream)	D_Q [m]	P_{Cu} [MW]	P_{beam} [MW]	$\Delta\psi_{x,y}$ [deg]	$\Delta\psi_z$ [deg]
0										
1	2.23	116.5	1.3613	0.6653	Q'/2 B V C' S W Q	0.0730	0.13	0.00		
2	0.00	116.5	0.3403	0.7951	Q B S W C'	0.7221	0.00	0.00		
			0.0000	0.8381	Q B W S C' T V S B Q/2	0.7651				
			1.7016	2.2984			0.13	0.00		
			4.0000				0.13			
1	8.07									
1		125.1	1.3814	0.1418	Q W C	0.1418	1.75	0.43		
2		133.8	1.4215	0.2628	T Q W	0.1460	1.88	0.44	77	109
3		142.8	1.4606	0.2703	B Q S	0.1501	1.93	0.45		
4		152.1	1.4987	0.2775	B Q S	0.1542	1.91	0.46	78	106
			5.7622	0.9524			7.47	1.78		
			6.7146				9.25			
2	7.85									
1		161.2	1.5353	0.2846	V Q W C	0.1581	1.72	0.46		
2		170.6	1.5704	0.2912	T Q W	0.1618	1.85	0.47	80	103
3		180.2	1.6047	0.2977	B Q 7S/6	0.1654	1.88	0.48		
4		190.0	1.6380	0.3041	B Q 7S/6	0.1689	1.88	0.49	80	101
			6.3484	1.1776			7.33	1.90		
			7.5260				9.23			
3	7.66									
1		199.7	1.6700	0.3102	V Q W C	0.1723	1.70	0.48		
2		209.5	1.7009	0.3161	T Q W	0.1756	1.82	0.49	81	98
3		219.6	1.7309	0.3218	B Q 7S/6	0.1787	1.86	0.50		
4		229.8	1.7600	0.3273	B Q 7S/6	0.1818	1.85	0.51	81	96
			6.8618	1.2754			7.23	1.98		
			8.1372				9.21			
4	7.48									
1		239.9	1.7881	0.3327	V Q W C	0.1848	1.68	0.51		
2		250.1	1.8151	0.3379	T Q W	0.1877	1.79	0.51	81	94
3		260.5	1.8414	0.3428	B Q 4S/3	0.1905	1.84	0.52		
4		271.1	1.8670	0.3477	B Q 4S/3	0.1932	1.83	0.53	80	92
			7.3116	1.3611			7.14	2.07		
			8.6728				9.21			
5	7.34									
1		281.5	1.8917	0.3524	V Q W C	0.1958	1.67	0.52		
2		292.1	1.9155	0.3570	T Q W	0.1983	1.78	0.53	80	90
3		302.8	1.9387	0.3614	B Q 4S/3	0.2007	1.83	0.53		
4		313.6	1.9613	0.3657	B Q 4S/3	0.2031	1.81	0.54	79	89
			7.7072	1.4365			7.09	2.12		
			9.1436				9.21			
6	7.20									
1		324.4	1.9830	0.3698	V Q W C	0.2054	1.66	0.54		
2		335.2	2.0039	0.3738	T Q W	0.2077	1.77	0.54	79	87
3		346.1	2.0244	0.3777	B Q 3S/2	0.2098	1.81	0.55		
4		357.1	2.0443	0.3815	B Q 3S/2	0.2119	1.79	0.55	78	85
			8.0555	1.5028			7.03	2.18		
			9.5583				9.21			
7	7.09									
1		368.1	2.0635	0.3852	V Q W C	0.2140	1.65	0.55		
2		379.1	2.0821	0.3887	T Q W	0.2159	1.76	0.55	77	84
3		390.2	2.1002	0.3921	B Q 3S/2	0.2178	1.80	0.56		
4		401.5	2.1179	0.3955	B Q 3S/2	0.2197	1.78	0.56	76	82
			8.3637	1.5614			6.99	2.22		
			9.9251				9.21			
Grand Total			52.1119	11.5656			50.27	14.25		
			63.6775				64.66			

Symbol	Device	Length [cm]
B	beam position monitor	3.00
C	current pickup	1.00
C'	bunch length monitor	30.00
Q	standard quadrupole	8.60
Q'	DTL quadrupole	16.76
S	steering trim magnet	6.00
T	toroid current monitor	3.10
V	vacuum gate valve	4.90
W	wire scanner	5.00

Note: Available for devices $3\beta\lambda/2 - 10$ cm.

400 Mev Linac Upgrade - Principal Mechanical Dimensions

30 April 1990

400 MeV Linac Upgrade - Principal Mechanical Dimensions

Module /Sect.	KE_{out} [MeV]	L_{rf} [m]	L_{sep} [m]	L_{cum} [m]	Devices (upstream)	D_Q [m]	L_{device} [m]	L_{cell} [m]	L_{gap} [m]
0									
1	116.5	1.36126	0.66526	2.02652	Q'/2 B C' V S W Q	0.07300	0.6478	0.08508	0.03717
2	116.5	0.34031	0.79508	3.16192	Q B S W C'	0.72208	0.5150	0.08508	0.03717
		0.00000	0.83808	4.00000	Q B W S T C' V S B Q/2	0.76508	0.7280		
		1.70157	2.29842						
1									
1	125.1	1.38139	0.14178	5.52318	Q/2 W C	0.14178	0.0920	0.08634	0.03782
2	133.8	1.42149	0.26285	7.20751	T Q W	0.14601	0.1560	0.08884	0.03911
3	142.8	1.46059	0.27027	8.93837	B Q S	0.15013	0.1760	0.09129	0.04038
4	152.1	1.49870	0.27751	10.71458	B Q S	0.15416	0.1760	0.09367	0.04162
		5.76217	0.95241						
2									
1	161.2	1.53531	0.28456	12.53445	V Q W C	0.15807	0.1740	0.09596	0.04282
2	170.6	1.57045	0.29123	14.39613	T Q W	0.16178	0.1560	0.09815	0.04397
3	180.2	1.60468	0.29774	16.29854	B Q 7S/6	0.16539	0.1860	0.10029	0.04509
4	190.0	1.63801	0.30407	18.24062	B Q 7S/6	0.16891	0.1860	0.10238	0.04619
		6.34845	1.17760						
3									
1	199.7	1.67006	0.31023	20.22091	V Q W C	0.17233	0.1740	0.10438	0.04725
2	209.5	1.70085	0.31608	22.23784	T Q W	0.17558	0.1560	0.10630	0.04827
3	219.6	1.73088	0.32178	24.29050	B Q 7S/6	0.17875	0.1860	0.10818	0.04927
4	229.8	1.76002	0.32733	26.37785	B Q 7S/6	0.18183	0.1860	0.11000	0.05024
		6.86181	1.27542						
4									
1	239.9	1.78810	0.33272	28.49867	V Q W C	0.18483	0.1740	0.11176	0.05118
2	250.1	1.81512	0.33786	30.65164	T Q W	0.18768	0.1560	0.11344	0.05209
3	260.5	1.84141	0.34285	32.83591	B Q 4S/3	0.19045	0.1960	0.11509	0.05297
4	271.1	1.86702	0.34772	35.05064	B Q 4S/3	0.19316	0.1960	0.11669	0.05384
		7.31164	1.36115						
5									
1	281.5	1.89170	0.35245	37.29479	V Q W C	0.19579	0.1740	0.11823	0.05467
2	292.1	1.91549	0.35697	39.56725	T Q W	0.19830	0.1560	0.11972	0.05547
3	302.8	1.93866	0.36137	41.86728	B Q 4S/3	0.20074	0.1960	0.12117	0.05626
4	313.6	1.96134	0.36566	44.19428	B Q 4S/3	0.20312	0.1960	0.12258	0.05703
		7.70719	1.43645						
6									
1	324.4	1.98297	0.36983	46.54707	V Q W C	0.20544	0.1740	0.12394	0.05777
2	335.2	2.00394	0.37381	48.92482	T Q W	0.20765	0.1560	0.12525	0.05848
3	346.1	2.02437	0.37769	51.32688	B Q 3S/2	0.20981	0.2060	0.12652	0.05918
4	357.1	2.04426	0.38147	53.75262	B Q 3S/2	0.21191	0.2060	0.12777	0.05986
		8.05553	1.50281						
7									
1	368.1	2.06350	0.38516	56.20127	V Q W C	0.21395	0.1740	0.12897	0.06052
2	379.1	2.08209	0.38869	58.67205	T Q W	0.21592	0.1560	0.13013	0.06116
3	390.2	2.10021	0.39213	61.16439	B Q 3S/2	0.21783	0.2060	0.13126	0.06178
4	401.5	2.11787	0.39548	63.67774	B Q 3S/2	0.21969	0.2060	0.13237	0.06239
		8.36367	1.56145						

Devices Needed in Inter-tank Spaces

Symbol	Device	Length [cm]
B	beam position monitor	3.00
C	current pickup	1.00
C'	bunch width monitor	30.00
Q	standard quadrupole	8.60
Q'	DTL quadrupole	16.76
S	steering trim magnet	6.00
T	toroid current monitor	3.10
V	vacuum gate valve	4.90
W	wire scanner	3.90

Note: Available for devices $3\beta\lambda/2 - 10$ cm.

400 Mev Upgrade Linac - RF Power Budget

30 April 1990

400 MeV Upgrade Linac - RF Power Budget

Module /Sect.	Grad. [MV/m]	KE_{out} [MeV]	L_{rf} [m]	P_{Cu} [MW]	P_{bridge} [MW]	P_{beam} [MW]	P_{total} [MW]
0							
1	2.23	116.5	1.3613	0.13	0.00	0.00	0.13
2	0.00	116.5	0.3403	0.00	0.00	0.00	0.00
				0.13	0.00	0.00	0.13
1	8.07						
1		125.1	1.3814	1.75	0.00	0.43	2.18
2		133.8	1.4215	1.77	0.11	0.44	2.32
3		142.8	1.4606	1.79	0.14	0.45	2.38
4		152.1	1.4987	1.80	0.11	0.46	2.37
				7.10	0.36	1.78	9.25
2	7.85						
1		161.2	1.5353	1.72	0.00	0.46	2.18
2		170.6	1.5704	1.74	0.11	0.47	2.32
3		180.2	1.6047	1.75	0.13	0.48	2.36
4		190.0	1.6380	1.77	0.11	0.49	2.37
				6.98	0.35	1.90	9.23
3	7.66						
1		199.7	1.6701	1.70	0.00	0.48	2.18
2		209.6	1.7009	1.71	0.11	0.49	2.31
3		219.6	1.7309	1.73	0.13	0.50	2.36
4		229.8	1.7600	1.74	0.11	0.51	2.36
				6.88	0.35	1.98	9.21
4	7.48						
1		239.9	1.7881	1.68	0.00	0.51	2.19
2		250.2	1.8151	1.69	0.10	0.51	2.30
3		260.6	1.8414	1.71	0.13	0.52	2.36
4		271.1	1.8670	1.72	0.11	0.53	2.36
				6.80	0.34	2.07	9.21
5	7.34						
1		281.6	1.8917	1.67	0.00	0.52	2.19
2		292.1	1.9155	1.68	0.10	0.53	2.31
3		302.8	1.9387	1.70	0.13	0.53	2.36
4		313.6	1.9612	1.71	0.10	0.54	2.35
				6.76	0.33	2.12	9.21
6	7.20						
1		324.4	1.9830	1.66	0.00	0.54	2.20
2		335.2	2.0039	1.67	0.10	0.54	2.31
3		346.1	2.0244	1.68	0.13	0.55	2.36
4		357.1	2.0443	1.69	0.10	0.55	2.34
				6.70	0.33	2.18	9.21
7	7.09						
1		368.1	2.0635	1.65	0.00	0.55	2.20
2		379.1	2.0821	1.66	0.10	0.55	2.31
3		390.2	2.1002	1.67	0.13	0.56	2.36
4		401.5	2.1179	1.68	0.10	0.56	2.34
				6.66	0.33	2.22	9.21
Grand Total				48.02	2.39	14.25	64.66

400 MeV Upgrade Linac - Kinematic and Dynamic Quantities

30 April 1990

400 MeV Linac Upgrade - Kinematic and Dynamic Quantities

Module /Sect.	KE_{out} [MeV]	L_{ef} [m]	γ	β	$\bar{\beta}$	$\beta\gamma$	$\Delta\psi_{x,y}$ [deg]	$\Delta\psi_z$ [deg]	$\hat{\beta}$ [m]	$\check{\beta}$ [m]	β_φ [deg/keV]
0									2.18	3.84	0.0500
1	116.54	1.3613	1.12421	0.456904	0.456904	0.513655					
2	116.54	0.3403	1.12421	0.456904	0.456904	0.513655					
1									8.65	1.06	0.0131
1	125.06	1.3814	1.13329	0.470527	0.463663	0.533244					
2	133.83	1.4215	1.14264	0.483816	0.477121	0.552826	77	109	8.11	0.98	0.0127
3	142.84	1.4606	1.15223	0.469773	0.490245	0.572398					
4	152.07	1.4987	1.16207	0.509398	0.503034	0.591957	78	106	8.33	1.03	0.0116
2											
1	161.25	1.5353	1.17186	0.521344	0.515325	0.610941					
2	170.63	1.5704	1.18186	0.532984	0.527119	0.629912	80	103	8.49	1.07	0.0109
3	180.21	1.6047	1.19207	0.544320	0.538609	0.648867					
4	189.98	1.6380	1.20248	0.555356	0.549796	0.667807	80	101	8.66	1.13	0.0101
3											
1	199.69	1.6701	1.21282	0.565829	0.560552	0.686251					
2	209.56	1.7009	1.22335	0.576027	0.570889	0.704680	81	98	8.78	1.18	0.0095
3	219.60	1.7309	1.23404	0.585954	0.580969	0.723093					
4	229.79	1.7600	1.24491	0.595616	0.590748	0.741490	81	96	8.92	1.24	0.0089
4											
1	239.91	1.7881	1.25569	0.604804	0.600174	0.759446					
2	250.17	1.8151	1.26662	0.613749	0.609241	0.777388	81	94	9.02	1.29	0.0085
3	260.56	1.8414	1.27770	0.622457	0.618069	0.795315					
4	271.09	1.8670	1.28893	0.630932	0.626662	0.813227	80	92	9.13	1.36	0.0080
5											
1	281.55	1.8917	1.30007	0.639024	0.634946	0.830779					
2	292.13	1.9155	1.31135	0.646903	0.642932	0.848317	80	90	9.22	1.42	0.0077
3	302.83	1.9387	1.32276	0.654574	0.650708	0.865842					
4	313.65	1.9613	1.33428	0.662044	0.658322	0.883354	79	89	9.31	1.49	0.0073
6											
1	324.36	1.9830	1.34570	0.669174	0.665580	0.900510					
2	335.18	2.0039	1.35724	0.676120	0.672619	0.917655	79	87	9.38	1.55	0.0071
3	346.11	2.0244	1.36888	0.682886	0.679476	0.934789					
4	357.13	2.0443	1.38063	0.689477	0.686155	0.951911	78	85	9.47	1.63	0.0068
7											
1	368.08	2.0635	1.39230	0.695797	0.692611	0.968755					
2	379.12	2.0821	1.40406	0.701957	0.698852	0.985590	77	84	9.53	1.69	0.0066
3	390.25	2.1002	1.41592	0.707959	0.704933	1.002414					
4	401.46	2.1179	1.42788	0.713809	0.710860	1.019230	76	82	9.62	1.79	0.0063

Numbers Derived from Energy and β_{geom}

400 MeV Linac - Numbers derived from Energy and $\bar{\beta}$ — 30 April 1990

W [MeV]	β	γ	$\beta \times \gamma$	$\bar{\beta}$	L_{rf} [m]	L_{sep} [m]	L_{sec} [m]	L_{cum} [m]	D_Q [m]	L_{cell} [cm]	L_{gap} [cm]	T	ZT^2 [MΩ/m]	E_{max} (E_o = 1 MV/m)
116.540	0.4569042	1.1242070	0.5136549	0.4569042	0.0000000	0.0000000	0.0000000	4.0000000	0.0000000	8.50785	3.71685	0.84288	36.028	4.485
125.064	0.4705271	1.1332915	0.5332444	0.4636630	1.3813930	0.1417834	1.5231763	5.5231762	0.1417834	8.63371	3.78171	0.84405	36.511	4.497
133.831	0.4838164	1.1426358	0.5528260	0.4771208	1.4214878	0.2628456	1.6843334	7.2075095	0.1460107	8.88430	3.91123	0.84623	37.440	4.522
142.835	0.4967732	1.1522324	0.5723981	0.4092452	1.4605894	0.2702693	1.7308587	8.9383678	0.1501346	9.12868	4.03801	0.84816	38.302	4.545
152.068	0.5093977	1.1620729	0.5919573	0.5030373	1.4987009	0.2775072	1.7762080	10.7145758	0.1541552	9.36688	4.16204	0.84987	39.101	4.566
					5.7621713	0.9524055	6.7145762							
161.249	0.5213445	1.1718572	0.6109414	0.5153251	1.5353101	0.2845595	1.8198696	12.5344458	0.1580728	9.59569	4.28159	0.85137	39.833	4.586
170.633	0.5329843	1.1818583	0.6299120	0.5271194	1.5704489	0.2912332	1.8616821	14.3961277	0.1617800	9.81531	4.39673	0.85268	40.501	4.604
180.213	0.5443201	1.1920691	0.6488671	0.5386087	1.6046789	0.2977354	1.9024143	16.2985420	0.1653920	10.02924	4.50925	0.85385	41.121	4.622
189.984	0.5553564	1.2024832	0.6678067	0.5497959	1.6380091	0.3040678	1.9420769	18.2406197	0.1689087	10.23756	4.61916	0.85489	41.697	4.639
					6.3484473	1.1775960	7.5260434							
199.686	0.5658294	1.2128234	0.6862511	0.5605521	1.6700550	0.3102329	1.9802879	20.2209072	0.1723344	10.43784	4.72516	0.85580	42.223	4.656
209.559	0.5760269	1.2233453	0.7046798	0.5708887	1.7008508	0.3160833	2.0169342	22.2378407	0.1755843	10.63032	4.82732	0.85660	42.706	4.672
219.596	0.5859540	1.2340434	0.7230927	0.5809689	1.7308829	0.3217798	2.0526628	24.2905045	0.1787487	10.81802	4.92722	0.85732	43.154	4.688
229.794	0.5956159	1.2449124	0.7414896	0.5907477	1.7600169	0.3273253	2.0873423	26.3778477	0.1818292	11.00011	5.02440	0.85796	43.568	4.703
					6.8618059	1.2754214	8.1372280							
239.907	0.6048038	1.2556906	0.7594464	0.6001737	1.7880999	0.3327226	2.1208224	28.4986706	0.1848274	11.17562	5.11831	0.85853	43.948	4.719
250.165	0.6137490	1.2666225	0.7773883	0.6092413	1.8151150	0.3378552	2.1529701	30.6516399	0.1876785	11.34447	5.20889	0.85904	44.297	4.734
260.561	0.6224568	1.2777035	0.7953152	0.6180689	1.8414149	0.3428522	2.1842670	32.8359070	0.1904544	11.50884	5.29728	0.85951	44.621	4.749
271.094	0.6309325	1.2889293	0.8132274	0.6266615	1.8670150	0.3477165	2.2147315	35.0506401	0.1931565	11.66884	5.38352	0.85993	44.921	4.764
					7.3116450	1.3611465	8.6727915							
281.552	0.6390242	1.3000746	0.8307791	0.6349463	1.8916979	0.3524512	2.2441490	37.2947884	0.1957866	11.82311	5.46687	0.86031	45.197	4.779
292.132	0.6469032	1.3113513	0.8483174	0.6429324	1.9154910	0.3569714	2.2724624	39.5672493	0.1982976	11.97182	5.54738	0.86066	45.450	4.793
302.833	0.6545745	1.3227557	0.8658422	0.6507084	1.9386580	0.3613727	2.3000307	41.8672791	0.2007425	12.11661	5.62594	0.86098	45.685	4.808
313.650	0.6620435	1.3342844	0.8833544	0.6583221	1.9613415	0.3656581	2.3269997	44.1942787	0.2031230	12.25838	5.70302	0.86129	45.904	4.823
					7.7071886	1.4364533	9.1436424							
324.365	0.6691743	1.3457040	0.9005105	0.6655803	1.9829658	0.3698304	2.3527963	46.5470734	0.2054408	12.39354	5.77665	0.86157	46.103	4.838
335.185	0.6761203	1.3572365	0.9176551	0.6726194	2.0039375	0.3738138	2.3777514	48.9248238	0.2076536	12.52461	5.84820	0.86183	46.287	4.853
346.109	0.6828862	1.3688791	0.9347887	0.6794760	2.0243654	0.3776940	2.4020593	51.3268814	0.2098090	12.65228	5.91802	0.86208	46.458	4.868
357.133	0.6894767	1.3806283	0.9519110	0.6861549	2.0442638	0.3814736	2.4257374	53.7526207	0.2119086	12.77665	5.98615	0.86232	46.616	4.883
					8.0555334	1.5028118	9.5583448							
368.080	0.6957971	1.3922955	0.9687552	0.6926112	2.0634992	0.3851551	2.4486544	56.2012749	0.2139537	12.89687	6.05212	0.86255	46.762	4.898
379.119	0.7019565	1.4040607	0.9855895	0.6988517	2.0820916	0.3886859	2.4707775	58.6720543	0.2159150	13.01307	6.11600	0.86278	46.896	4.913
390.248	0.7079588	1.4159217	1.0024141	0.7049331	2.1002100	0.3921265	2.4923365	61.1643906	0.2178263	13.12631	6.17835	0.86299	47.020	4.927
401.464	0.7138085	1.4278760	1.0192300	0.7108598	2.1178672	0.3954796	2.5133469	63.6777382	0.2196889	13.23667	6.23921	0.86321	47.135	4.942
					8.3636684	1.5614470	9.9251156							