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Computational Research on Beam Transverse Motion for 35 Mev Beijing Proton Linac

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Some problems related to the beam dynamics computation of the transverse motion for the 35 MeV Beijing Proton Linac are discussed. The suitability and reliability of the computations are proved. These computations are useful for guiding the beam testing of the linac.

1. INTRODUCTION

The 35 Mev Beijing Proton Linac (BPL) was constructed on the basis of the 10 MeV proton linac without changing the 10 MeV accelerating structure. However, it is different from the 10 MeV linac in terms of distribution of the average electric field on axis, the synchronous phase law, the number of transverse focusing quadruples and their division. Therefore, the transverse beam dynamics calculation should be re-done by taking into account some new conditions. In this paper we have discussed this problem and got the transverse focusing structure parameters, quadrupole power supplies distribution and the quadrupole gradients which meet the transverse beam matching, thus providing relevant parameters for the fabrication of quadruples and their power supplies, the system integration test and beam production.

2. TRANSVERSE FOCUSING STRUCTURE AND QUADRUPLE GROUPS

In the 35 MeV proton linac, the FD mode is used as the transverse focusing structure. Since this mode has a bigger transverse stable region, stronger focusing and less change

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TABLE 1
Parameter List of Drift-Tube Quadrupoles

Group No.	No. of quad	Num. of quad	Core length (cm)	Effective length (cm)	Max. grad. (Wb/m³)	Peak cur. (A)	Grad./IN (Wb/m³ A)	Inner diameter (cm)
1	1—8	8	2.54	3.45	92	212	41.38×10^{-2}	2.2
2	9—18	10	3.17	4.09	72	166	41.88×10^{-2}	2.2
3	19—35	17	4.44	5.64	52	230	21.85×10^{-2}	2.9
4	36—56	21	6.98	8.20	34	151	21.84×10^{-2}	2.9
5	57—105	49	10.16	11.38	20	192	10.77×10^{-2}	3.4

in the beam envelope along the cavity, the space charge effect can be easily overcome and the beam loss prevented.

There are 105 drift-tube quadrupoles in the 35 MeV cavity, which are divided into 5 groups according to their lengths. This arrangement is suitable for quadruple fabrication and their replacement and keeping better focusing performance. These quadrupole parameters are listed in Table 1.

3. TRANSVERSE FOCUSING OR DEFOCUSING PARAMETERS AND WORKING POINTS

The transverse stable diagram for FD mode is shown in Fig. 1. The vertical and horizontal coordinates in this figure are the focusing parameter and defocusing parameter respectively, with

$$\theta^2 = eH'L_c^2/(m_0c\beta_s\gamma_s); \tag{1}$$

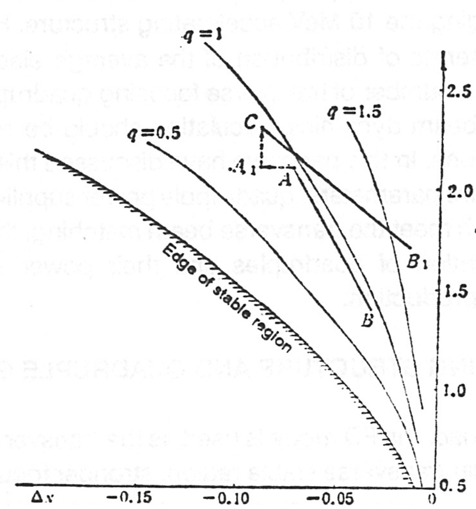

FIG. 1 FD mode's stable diagram and working line of synchronous particles in the 35 MeV linac.

$$\Delta_N = \pi e E_1 T \sin \varphi_s L_c^2 / (m_0 c^2 \beta_s^3 \gamma_s^3 \lambda), \quad (2)$$

Where H' is gradient (Wb/m^3), L_c is accelerating cell length (cm), m_0c^2 is the rest mass of proton (MeV), β_s is the synchronous particle's velocity in the unit of light velocity $\gamma_s = (1 - \beta_s^2)^{-1/2}$, E_1 is average electric field on axis (MV/m), T is the transit time factor, φ_s is RF synchronous phase (°), λ is RF wave length (m).

From Eq. (2) one can see that Δ_N depends on E_1, T, φ_s and so on. Fig. 2 shows these parameters' variations along the accelerating cavity. The transit time factor T has its jumps at n_c = 18 and n_c = 57, where the inner or outer diameters of drift-tube and the cavity diameter are changed. E_1 increases with the cell number, and it has the values of 1.65 MV/m and 2.6 MV/m in the first and last cells respectively. The synchronous phase is increased gradually from −40° at the first cell to −25° at the last cell, and at cell number 54, it has the maximum value of −23.6° when the electric field law is re-chosen and the original 10 MeV cavity structure remains unchanged. This phase law is entirely permissible to accelerate 100 mA beam current[1].

After the completion of extending the 10 MeV to 35 MeV, E_1 becomes higher and the $|\varphi_s|$ becomes larger at the front end of the linac. From Eq. (2) it can be seen that the RF defocusing becomes stronger and that Δ_N changes from its original value of −0.076 to the new one of −0.091. In this case, if one doesn't change the gradient value of drift-tube quadruple, then the synchronous working point will move from point A to A_1 as shown in Fig. 1, i.e. the working point will move towards the edge of the stable region. The original 10 MeV working line AB is also shown in Fig. 1. To increase the beam stability in the transverse motion and to allow all of the nonsynchronous particles located in the longitudinal stable region $3|\varphi_s|$, also to be accepted by the transverse stable region in the

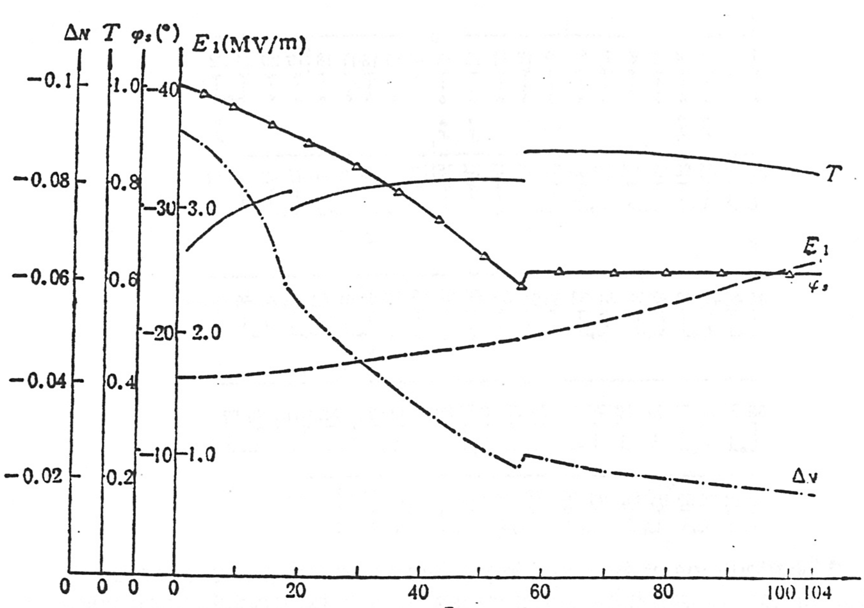

FIG. 2 Some parameters of the 35 MeV linac versus cell number n_c.

case of smaller $\varphi_s = -40°$, one should enhance the quadruple gradient and move the starting point of the working line to point C as shown in Fig. 1, where CB_1 is the working line of synchronous particle in 35 MeV linac. This working line has an advantage of avoiding the most dangerous transverse and longitudinal coupling resonant line $q = 0.5$ as shown in Fig. 1, and passing fast through the $q = 1$ and $q = 1.5$ resonant lines so that a great number of particles can be prevented from losing. The quadruple gradients and the peak currents of their power supplies corresponding to this working line make it easier to manufacture and adjust the power supplies.

4. BEAM MATCHING

The beam matching in transverse motion of proton linac is performed by adjusting the gradients of some quadruples, which are used as matching elements, so that the emittance ellipse parameters are the same as the machine acceptance at the matching point. The calculation for beam matching is described in detail in Ref. [2].

In the 35 MeV Beijing Proton Linac, the drift-tube quadruple lengths are changed between the adjacent groups, so the focusing parameters are changed there in a discontinuous way. At the same time, the defocusing parameter Δ_N is also changed in a discontinuous way some where as shown in Fig. 2. These discontinuities produce the beam mismatching in transverse motion. To make the beam matching, we choose some drift-tube quadruples as matching elements, which are located at each end of the cavity and that of each quadruple group. The calculated results show that if we choose the vertical matching points which are different from the horizontal ones and select both of

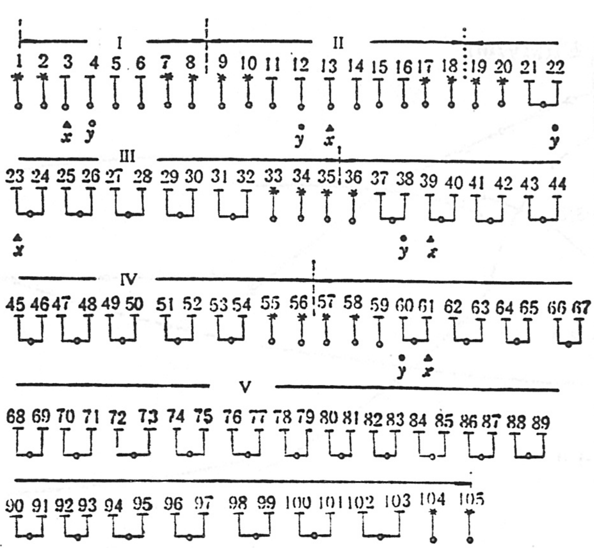

FIG. 3 Distributions of the matching points and quad. power supplies. 1) 1, 2... number of drift-tube quadrupoles. 2) ▲, • horizontal(x) and vertical(y) beam matching points. 3) * quadrupoles act as matching elements. 4) Ī ⊔ quadrupoles powered individually and in pairs mode.

TABLE 2
The Computed Gradient Values and Matched Beam Envelope

Beam intensity $I_b = 60\,\mathrm{mA}$

No. of quad	$H'(\mathrm{Wb/m^3})$	$Y_e(\mathrm{mm})$	$X_e(\mathrm{mm})$	No. of quad	$H'(\mathrm{Wb/m^3})$	$Y_e(\mathrm{mm})$	$X_e(\mathrm{mm})$
1	83.88	2.987	4.994	45	24.62	4.692	6.687
2	81.54	5.026	3.029	46	24.62	6.874	4.605
3	80.89	3.045	5.047	47	24.20	4.732	6.737
4	80.03	5.077	3.027	48	24.20	6.877	4.644
5	79.02	3.054	5.028	49	23.84	4.733	6.781
6	78.03	5.083	3.049	50	23.84	6.879	4.695
7	75.63	3.195	5.066	51	23.51	4.744	6.830
8	76.10	5.369	3.156	52	23.51	6.874	4.755
9	64.73	3.334	5.310	53	23.39	4.708	6.987
10	64.46	5.407	3.347	54	23.39	6.513	5.296
11	62.54	3.378	5.443	55	21.29	4.720	7.805
12	61.91	5.443	3.403	56	23.74	7.286	5.032
13	61.24	3.390	5.478	57	18.31	5.099	6.664
14	60.50	5.453	3.421	58	15.66	6.866	4.802
15	59.79	3.436	5.496	59	16.54	4.763	6.925
16	59.06	5.565	3.473	60	17.55	6.847	4.802
17	57.63	3.623	5.559	61	17.55	4.745	6.873
18	58.50	5.828	3.560	62	17.36	6.797	4.771
19	43.09	3.814	5.658	63	17.36	4.718	6.851
20	43.44	5.945	3.714	64	17.22	6.791	4.772
21	41.99	3.891	5.793	65	17.22	4.734	6.880
22	41.99	5.983	3.789	66	17.06	6.831	4.806
23	40.80	3.924	5.827	67	17.06	4.764	6.923
24	40.80	6.007	3.829	68	16.90	6.854	4.824
25	39.89	3.963	5.895	69	16.90	4.765	6.913
26	39.89	6.078	3.911	70	16.77	6.830	4.795
27	39.05	4.048	6.027	71	16.77	4.740	6.852
28	39.05	6.209	4.016	72	16.66	6.798	4.752
29	38.28	4.148	6.146	73	16.66	4.729	6.816
30	38.28	6.317	4.086	74	16.55	6.803	4.754
31	37.58	4.207	6.197	75	16.55	4.745	6.854
32	37.58	6.354	4.117	76	16.44	6.832	4.796
33	36.45	4.300	6.182	77	16.44	4.764	6.908
34	36.44	6.484	4.191	78	16.34	6.843	4.814
35	36.72	4.373	6.311	79	16.34	4.760	6.893
36	26.58	6.510	4.302	80	16.28	6.827	4.773
37.	26.54	4.429	6.402	81	16.28	4.742	6.818
38	26.54	6.538	4.352	82	16.22	6.807	4.726
39	26.02	4.454	6.427	83	16.22	4.733	6.788
40	26.02	6.574	4.381	84	16.14	6.803	4.741
41	25.59	4.502	6.485	85	16.14	4.737	6.849
42	25.59	6.662	4.451	86	16.04	6.807	4.799
43	25.11	4.596	6.593	87	16.04	4.744	6.911
44	25.11	6.790	4.542	88	15.94	6.809	4.815

TABLE 2
Continued

Beam intensity $I_b = 60\,mA$							
No. of quad	$H'(Wb/m^3)$	$Y_e(mm)$	$X_e(mm)$	No. of quad	$H'(Wb/m^3)$	$Y_e(mm)$	$X_e(mm)$
89	15.94	4.745	6.874	98	15.69	6.788	4.800
90	15.88	6.808	4.757	99	15.69	4.734	6.846
91	15.88	4.744	6.775	100	15.67	6.799	4.730
92	15.85	6.807	4.700	101	15.67	4.739	6.737
93	15.85	4.740	6.746	102	15.64	6.800	4.677
94	15.80	6.800	4.724	103	15.64	4.732	6.722
95	15.80	4.734	6.828	104	15.63	6.782	4.706
96	15.74	6.788	4.791	105	15.62	4.732	6.722
97	15.74	4.729	6.897				

Note: H' is the gradient which meets the matching condition, X_e and Y_e are the horizontal and vertical beam envelopes respectively in the middle of each quadruple.

them at the locations where the envelope functions of the focusing structure have their minimum values, then the influence of gradient error on beam matching will not be sensitive and the beam matching will become easy.

The drift-tube quadrupoles are powered in two modes: each of the first 18 quadrupoles and each matching quadrupole are powered individually, all the others are powered in pairs. These power modes save money and also make the beam matching easy.

The matching points and the quadruple power supplies for 35 MeV Beijing Proton Linac are distributed as shown in Fig. 3.

5. MATCHING COMPUTATION RESULTS

By using the program LAM in which the linear space charge effect was taken into account, we computed the beam matching with the working line mentioned above. In this computation, the matching quadruple gradients are automatically obtained through the computer according to the given beam current (i.e. space charge force) and the matching requirement. The computed gradient values and the corresponding beam envelope are listed in Table 2.

We checked the computed results by using the multi-particle simulation program PARMILA in which the nonlinear coupling effects produced both from outer field and self-field (space charge effect) were taken into account. This check shows the multi-particle motions in the matching condition mentioned-above. It also shows the normalized emittance growth and particles loss in the course of acceleration. The checked results are that all of the 500 representative particles are transmitted through the linac and the normalized emittance has grown by a factor of 2.2 within the energy of 10 MeV as shown in Fig. 4, where ε_0 is the normalized emittance at the input of the linac. This growth factor

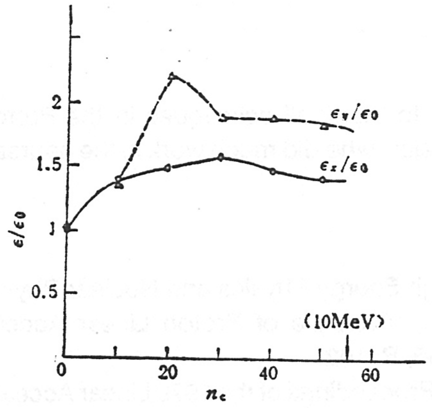

FIG. 4 Beam emittance growth within the energy of 10 MeV, computed with PARMILA program.

is in full agreement with many experimental or operation results obtained in other countries[4]. It means the matching computation for the 35 MeV proton linac is reliable.

6. BEAM TEST RESULTS

The 35 MeV Beijing Proton Linac produced its first beam in August, 1985 with the computed parameters mentioned above. After adjusting carefully some drift-tube quadrupole gradients and the RF input power into cavity, we got the optimum operation parameters. In November, 1985, the 35.6 MeV proton beam with a pulse current of 70 mA at the output of the linac was obtained, and its transmission efficiency reached up to about 60%.

From the beam test experiments we got the following points: 1) The drift-tube quadrupole gradient values play a very important role in the beam current at the output of the linac, it is particularly so within 10 MeV region. 2) The first beam was successfully obtained with the designed or computed gradients, it means that the matching computation is reasonable and reliable. 3) Due to the fact that it is impossible to take into account all the real conditions and effects in the computation, one should carefully adjust the quadrupole gradients to set up the optimum operation condition and get the maximum beam current at the output of the linac. 4) In addition to the quadrupole gradients, there are still many other elements which affect the beam current, such as the RF input power, the electric field distribution along the cavity, the injected particle's energy and emittance and so on. At the beginning of each operation, all the elements mentioned above cannot be fully repeated, therefore one should re-adjust some quadrupole gradients to meet the new conditions. 5) We obtained the beam transmission rate of 60% with single buncher. It is difficult to get this rate in the case of our long cavity (22m). This is the weakness of the proton linac which has long cavities.

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