TRANSVERSE MATCHING IN J-PARC LINAC COMMISSIONING

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Abstract

Transverse matching has been performed at J-PARC LINAC for matching sections at DTL-SDTL, S01A-S03B, MEBT2-ACS, and L3BT. Each matching section consists of 4 wire scanners and upstream 4 quadrupole magnets. From r.m.s. of beam profiles measured at 4 wire scanners, transverse Twiss parameters and emittance are fitted with Newton method based on an online model. Field of quadrupole magnets with matching conditions is calculated based on the model. At beam current of 5mA and 25mA, matching factors of within 4% were achieved.

INTRODUCTION

To measure beam profiles, 36 wire scanners (WS's) are installed as shown in Fig. 1 [1]. There are 8 matching sections each of which consists of 4 WS's which fulfil periodic envelope conditions and upstream 4 singlet quadrupole magnets (QM's) for tuning. A WS has a horizontal (x) and a vertical (y) wires. Each wire moves perpendicularly to the wire with stepping motors. A Carbon wire of 7 μm-diameter is used at MEBT1 at 3 MeV, and a 30 μm-diameter tungsten wire is used at downstream sections at 50-180 MeV in order to capture electrons of H^- beam efficiently. Stepping motors and data acquisition are controlled in an EPICS control system.

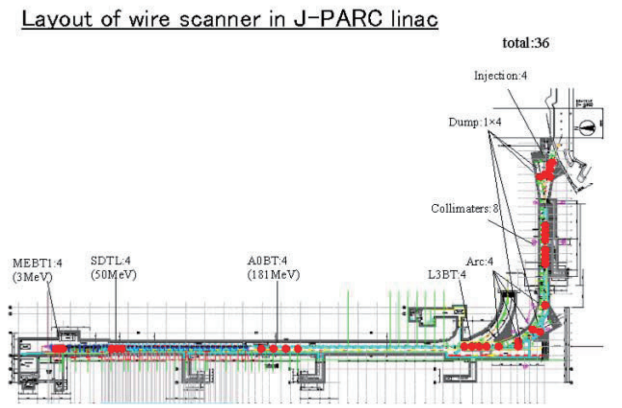

Fig. 1: Locations of wire scanners in J-PARC LINAC.

METHOD OF TUNING

Table 1 shows QM's and WS's. Since WS's at MEBT1 have no periodic envelope condition, matching procedure how and which QM's to be used has not been established. The r.m.s. of beam profile is obtained with 4 WS's in one of the matching sections. If one of the WS's is not available, the other 3 WS data are used. We compared results of matching with σ of Gaussian fit, but there is no essential difference, except that calculated emittance value by r.m.s. is larger than that calculated from the σ by a few %, due to difference between the r.m.s. and the σ. The procedure of calculating QM field from measured beam profile is as follows.

1. We first fit Twiss parameters ($\alpha_x, \alpha_y, \beta_x, \beta_y$) and emittance ($\varepsilon_x,\varepsilon_y$) at the entrance of a section to the measured r.m.s. of 4 (or 3) WS's in the x- and y-directions with a XAL model [2]. The fitting is done with a Newton method (or a response matrix method). In this method, with m fit parameters x_i ($i=1,\dots,m$) and n goal parameters y_j ($j=1,\dots,n$) with goal values Y_j, the correction for x_i, Δx_i to make y_j into Y_j is estimated with;
$$\begin{pmatrix} \Delta y_1 \\ \Delta y_2 \\ \vdots \\ \vdots \\ \Delta y_n \end{pmatrix} = \begin{pmatrix} \frac{\partial y_1}{\partial x_1} & \frac{\partial y_1}{\partial x_2} & \frac{\partial y_1}{\partial x_3} & \cdots & \cdots & \frac{\partial y_1}{\partial x_m} \\ \frac{\partial y_2}{\partial x_1} & \frac{\partial y_2}{\partial x_2} & & & & \vdots \\ \vdots & & & & & \vdots \\ \vdots & & & & & \vdots \\ \frac{\partial y_n}{\partial x_1} & \cdots & \cdots & \cdots & \cdots & \frac{\partial y_n}{\partial x_m} \end{pmatrix} \begin{pmatrix} \Delta x_1 \\ \Delta x_2 \\ \vdots \\ \vdots \\ \vdots \\ \Delta x_m \end{pmatrix},$$
where $\Delta y_j = Y_j - y_j$. The matrix in the equation is called a response matrix (RM) which is the Jacobian $(\partial y/\partial x)$. Δx_i can be solved with a pseudo-inverse matrix of the RM calculated with Singular Value Decomposition (SVD) technique [3]. $\Delta \mathbf{x} = \left(\frac{\partial y}{\partial x}\right)^{-1} \Delta \mathbf{y}$. With SVD, calculation errors are treated automatically, and when $m < n$, the correction serves as fitting. The correction in Δx_i is applied iteratively until optimum point is found. The number of iterations with Newton method is 2~3 while it is ~40 with Simplex method [3] to minimize χ^2 of Δy_j in Twiss parameter fitting. This is why we adopt Newton method. If y_j can be measured and x_i can be controlled, RM can be obtained with measurements. However, it is often not the case, and even when possible it may take too long time. In the present procedure, RM is calculated with the model.

   For fitting of Twiss parameters and emittance, x is defined as; $\mathbf{x} = (\alpha_x, \alpha_y, \beta_x, \beta_y, \varepsilon_x, \varepsilon_y)$ and y is defined as;
$$\Delta \mathbf{y} = (\sigma_{xm}^1 - \sigma_x^1, \dots, \sigma_{xm}^{Nx} - \sigma_x^{Nx}, \sigma_{ym}^1 - \sigma_y^1, \dots, \sigma_{ym}^{Ny} - \sigma_y^{Ny})$$
where σ_{xm}^i is measured r.m.s. of the i-th WS.
2. Using the fitted Twiss parameters and emittance at the entrance of the matching section, we calculate corrections for QM field to fulfil the matching condition. The matching condition is defined so that ($\alpha_x, \alpha_y, \beta_x, \beta_y$) at each WS agrees with the others taking into account acceleration between WS's at SDTL. At MEBT2-ACS03 W1 does not fulfil the matching condition in the design so was not used. For other matching sections except for MEBT1, 4 WS's are

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Table 1: Quadruple magnets and wire scanners for beam profile measurements at each matching section

	MEBT1	DTL3-S03B	S01A-S03B	MEBT2-ACS03B	L3BT
Q1	-	LI_DTL3:DTQ23	LI_S01A:QM01	LI_MEBT2:QM01	LI_L3BT:QM01
Q2	-	LI_DTL3:DTQ24	LI_S01A:QM02	LI_MEBT2:QM02	LI_L3BT:QM02
Q3	-	LI_DTL3:DTQ27	LI_S01B:QM01	LI_MEBT2:QM03	LI_L3BT:QM03
Q4	-	LI_DTL3:DTQ28	LI_S01B:QM02	LI_MEBT2:QM04	LI_L3BT:QM04
W1	LI_MEBT1:WSM01	LI_S02A:WSM01	LI_S02A:WSM01	LI_MEBT2:WSM11	LI_L3BT:WSM06
W2	LI_MEBT1:WSM03A	LI_S02B:WSM01	LI_S02B:WSM01	LI_ACS01B:WSM01	LI_L3BT:WSM08
W3	LI_MEBT1:WSM03B	LI_S03A:WSM01	LI_S03A:WSM01	LI_ACS02B:WSM01	LI_L3BT:WSM10
W4	LI_MEBT1:WSM07	LI_S03B:WSM01	LI_S03B:WSM01	LI_ACS03B:WSM01	LI_L3BT:WSM12

used. The field corrections are also calculated with the Newton method. The fit parameters and goal parameters are defined as; $\mathbf{x} = (G_1, G_2, G_3, G_4)$, and

$$\mathbf{y} = (\alpha_x^1 - \alpha_x^2, \alpha_x^1 - \alpha_x^3, \alpha_x^1 - \alpha_x^4, \alpha_y^1 - \alpha_y^2, \alpha_y^1 - \alpha_y^3, \alpha_y^1 - \alpha_y^4, \beta_x^1 - \beta_x^2, \beta_x^1 - \beta_x^3, \beta_x^1 - \beta_x^4, \beta_y^1 - \beta_y^2, \beta_y^1 - \beta_y^3, \beta_y^1 - \beta_y^4)$$

RESULTS

We applied the above matching procedure at beam current of 5mA in April, at 25mA in May. The order of tuning was from upstream to downstream; DTL3-S03B (5mA) or S01A-S03B (25mA), MEBT2-ACS03B, and L3BT. R.m.s. at MEBT1 were also measured.

DTL3-S03B and S01A-S03B sections

Table 1 shows the designed and measured r.m.s. and mismatch factors defined as M=(σ_{max}- σ_{min})/(σ_{max}+ σ_{min}) where σ_{max} and σ_{min} are maximum and minimum r.m.s. of 4 WS's. At SDTL, a beam energy correction was applied. At 25mA, since tuning with QM's at DTL3 did not work well, QM's at SDTL are used. The mismatch factor is 2~3% after tuning. Table 2 shows QM field. Table 3 shows Twiss parameters and emittance. The units are same as TRACE3D; α(dimensionless), β(mm/mrad), ε(5 σ, πmm-mrad).

Table 1: Designed and measured r.m.s. (mm) and mismatch factors before and after tuning at SDTL.

	5mA (Apr 2007)			25mA (May 2007)		
Rms	design	uncor	cor	design	uncor	cor
σ_{1x}	1.725	1.79	1.67	2.127	2.79	2.46
σ_{2x}	1.758	1.76	1.61	2.162	2.94	2.38
σ_{3x}	1.735	1.59	1.55	2.157	2.59	2.30
σ_{4x}	1.679	1.52	1.61	2.144	2.09	2.36
M_x	2.98%	4.63%	3.23%	4.42%	14.3%	2.62%
σ_{1y}	1.531	-	-	1.977	-	-
σ_{2y}	1.540	1.76	1.65	1.925	2.52	2.32
σ_{3y}	1.559	1.79	1.56	1.919	2.52	2.31
σ_{4y}	1.548	1.57	1.61	1.983	2.24	2.27
M_y	2.95%	5.25%	2.91%	4.18%	4.56%	1.62%

Table 2: QM field values (T/m) at DTL3-S03B at 5mA and S01A-S03B at 25mA.

	5mA (Apr 2007)		25mA (May 2007)	
	uncor/design	cor (T/m)	uncor/design	cor (T/m)
Q1	-3.3916	-3.7291	-12.921	-11.416
Q2	6.1613	7.2707	12.921	11.292
Q3	-12.438	-12.197	-13.072	-14.575
Q4	11.480	10.743	13.072	14.349

Table 3: Fitted Twiss parameters and emittance before and after tuning at 5mA and 25mA.

	5mA (Apr 2007)			25mA (May 2007)		
	design	uncor	cor	design	uncor	cor
α_x	1.698	1.645	1.452	-0.0137	0.4318	0.3744
α_y	-1.814	-2.480	-2.169	2.300	2.564	2.705
β_x	1.984	1.846	1.595	4.338	2.879	2.737
β_y	2.034	2.700	2.518	8.032	7.143	7.416
ε_x	4.435	4.255	4.032	3.549	6.121	6.094
ε_y	3.552	3.663	4.054	2.890	5.406	5.335

MEBT2-ACS03B section

Tables 4-6 show r.m.s., QM field, Twiss parameters and emittance. The mismatch factor is 3~4% at 5mA and 1% at 25mA. Fig. 2 shows envelopes before and after tuning. The shapes of envelopes are periodic after tuning.

Table 4: The designed and measured r.m.s. (mm) and mismatch factors at MEBT2-ACS03B.

	5mA (Apr 2007)			25mA (May 2007)		
Rms	design	uncor	Cor	design	uncor	Cor
σ_{1x}	1.350	1.408	1.157	1.364	1.47	1.647
σ_{2x}	1.408	1.092	1.193	1.421	1.96	1.770
σ_{3x}	1.404	1.142	1.192	1.402	1.70	1.805
σ_{4x}	1.459	1.484	1.223	1.446	1.72	1.781
M_x	2.63%	15.2%	2.76%	2.89%	7.1%	0.96%
σ_{1y}	1.317	1.424	1.309	1.330	1.69	1.820
σ_{2y}	1.261	1.178	1.199	1.297	1.83	1.824
σ_{3y}	1.264	1.128	1.213	1.299	1.81	1.813
σ_{4y}	1.300	1.404	1.259	1.286	1.72	1.793
M_y	2.20%	11.6%	4.40%	0.48%	3.10%	0.86%

Table 5: QM field (T/m) at MEBT2-ACS03B.

	5mA (Apr 2007)		25mA (May 2007)	
	uncor/design	cor(T/m)	uncor/design	cor(T/m)
Q1	-16.099	-15.951	-14.6564	-16.2136
Q2	15.837	15.318	14.2021	15.7487
Q3	-8.893	-2.683	-4.2678	-4.7433
Q4	9.084	3.383	4.9369	5.3495

Table 6: Twiss parameters at MEBT2-ACS03B.

	5mA (Apr 2007)	25mA (May 2007)

	design	uncor	cor	design	uncor	cor
α_x	-0.5190	-0.6228	-0.6354	-0.4204	-0.6239	-0.6480
α_y	0.2003	0.3270	0.3831	0.7386	0.3717	0.2288
β_x	7.796	11.603	11.989	12.181	11.515	10.592
β_y	6.361	8.563	8.847	10.771	8.3234	8.0915
ε_x	1.926	1.356	1.382	1.8065	2.3234	2.9413
ε_y	1.543	1.406	1.437	1.4709	2.9091	3.0323

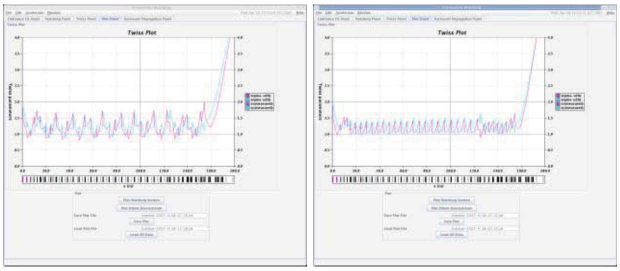

Fig. 2: Measured r.m.s. and fitted envelope in x- and y-directions before (left) and after (right) matching correction from MEBT2 section to the 0-degree dump.

L3BT section

Tables 7-9 show r.m.s., QM field, Twiss parameters and emittance before and after tuning at L3BT. The mismatch factor is 1~2% at 5mA and 0.2~0.7% at 25mA.

Table 7: The designed and measured r.m.s. (mm) and mismatch factors before and after corrections at L3BT.

	5mA (Apr 2007)			25mA (May 2007)		
rms	design	uncor	cor	design	uncor	cor
σ_{1x}	1.579	1.291	1.357	1.531	1.869	2.059
σ_{2x}	1.585	1.345	1.381	1.552	2.160	2.063
σ_{3x}	1.582	1.433	1.356	1.572	2.300	2.067
σ_{4x}	1.576	1.359	1.332	1.552	2.009	2.062
M_x	0.29%	5.20%	1.80%	1.31%	10.4%	0.194%
σ_{1y}	1.096	1.124	1.090	1.072	1.496	1.581
σ_{2y}	1.094	1.059	1.079	1.085	1.572	1.574
σ_{3y}	1.091	1.064	1.090	1.097	1.678	1.595
σ_{4y}	1.092	1.111	1.094	1.083	1.610	1.588
M_y	0.23%	2.98%	0.70%	1.14%	5.8%	0.68%

Table 8: QM field at L3BT.

	5mA (Apr 2007)		25mA (May 2007)	
	uncor/design	cor(T/m)	uncor/design	cor(T/m)
Q1	-3.9589	-4.2388	-3.6585	-4.3817
Q2	4.1188	4.3051	3.8850	4.4457
Q3	-5.1579	-5.2592	-5.3922	-5.2184
Q4	4.7557	4.8664	5.0489	4.7992

Table 9: Twiss parameters and emittance at L3BT.

	5mA (Apr 2007)			25mA (May 2007)		
	design	uncor	cor	design	uncor	cor
α_x	-0.1321	-0.2147	-0.2378	-0.0602	-0.2519	-0.2527
α_y	0.5421	0.5411	0.5301	0.5779	0.4451	0.4789
β_x	4.610	4.402	4.547	4.398	4.367	4.434
β_y	6.661	6.249	6.168	6.480	6.225	6.226
ε_x	1.926	1.405	1.411	1.807	3.251	3.259
ε_y	1.543	1.529	1.527	1.471	3.225	3.226

Measurements at MEBT1

Table 10 shows measured r.m.s., Twiss parameters and emittance at MEBT1. Tuning was not done at MEBT1.

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Table 10: The designed and measured r.m.s., fitted Twiss parameters and emittance at MEBT1.

	5mA		25mA	
Rms	design	uncor	design	uncor
σ_{1x}	0.928	0.937	1.045	1.07
σ_{2x}	2.483	1.745	2.933	2.14
σ_{3x}	1.012	1.012	1.391	1.51
σ_{4x}	1.685	-	2.062	-
σ_{1y}	1.523	1.70	1.530	1.70
σ_{2y}	0.699	0.644	1.153	1.26
σ_{3y}	2.438	1.918	2.969	2.91
σ_{4y}	1.084	1.569	1.167	-
α_x	-1.219	-1.840	-1.2187	-1.702
α_y	2.189	3.558	2.1885	3.0274
β_x	0.1317	0.1650	0.1317	0.1803
β_y	0.2234	0.2857	0.2234	0.2732
ε_x	15.655	10.925	15.655	14.682
ε_y	12.538	9.1978	12.538	11.954

SUMMARY

A matching procedure with the response matrix based on a model has been developed and applied to J-PARC LINAC. The procedure worked well except for a few cases (such as DTL3-S03B at 25mA). The mismatch factor was within 4% at SDTL, MEBT2-ACS03B, and L3BT at 5mA and 25mA. The emittance is consistent with the model at 5mA. At 25mA emittance is consistent with the model at MEBT1, but larger by a factor of 2 at the matching sections, which is under study. During a beam test at 25mA, a problem of beam orbit shifts was found due to charge-up and discharge of WS frame at SDTL. Since the problem might have affected WS data, the results will be compared after replacing the frames.

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