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Beam Matching Design of JHF Linac

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ABSTRACT

JHF/JAERI linac consists of RFQ, DTL, SDTL and ACS accelerators in its normal conducting section. As a high current proton accelerator, it requires very low beam losses in order to minimize the induced radioactivity to an acceptable level. Beam matching between the different accelerator sections is one of the key points to reduce the beam losses and emittance growth. A matching design study has been performed for the beam lines between the different type of normal-conducting accelerating structures. In this paper, we will present some details of the study, including the beam-line design by TRACE3-D code and multiparticle simulations of the beam behavior in different matching conditions.

1. INTRODUCTION

JHF/JAERI joint project proposed a proton accelerator complex with a 400-MeV linac, a 3-GeV rapid-cycling ring and a 50-GeV main ring. The linac provides an intense H^- beam with the peak current of 50 mA and an average current of 350 μA in the initial stage (700 μA in the upgrading plan). Therefore, beam-loss control is a very essential requirement in the accelerator design, because the lost particles on the machine will induce a radioactivity, which prevents the necessary manual maintenance during the long-term operation of the machine.

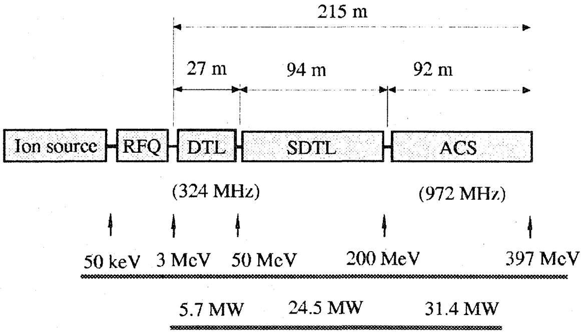

Fig.1 Schematic plot of JHF/JAERI intense beam H^- linac (normal conducting part).

The normal conducting part of JHF/JAERI linac consists of several different types of accelerating structures [1], as shown in Fig.1. RFQ, DTL and SDTL use the same RF frequency of 324 MHz. The final accelerating structure ACS has an RF frequency of 972 MHz and provides a beam of 400 MeV for the injection into the 3-GeV ring. Between these accelerating structures, there are beam transport lines. It has been realized that beam matching is of great significance for minimizing the emittance growth and avoiding beam-halo formation, which has been recognized as one of the major causes for beam losses[2]. Therefore, one of the main tasks of these beam lines is to match the beam from the preceding structure to the following one in both transversal and longitudinal directions.

In this paper, a study on the matching design of the beam transport lines is described. TRACE3-D[3] code is applied in the design of these beam lines. And the designed beam lines are simulated by the multiparticle codes LINSAC[4] and PARMILA[5], in order to check the beam behavior under various matching conditions. In the second section, we will present the design of the MEBT with two RF-choppers. The beam line between DTL and SDTL is discussed in the third section. In section four, design on HEBT will be described. Finally, some conclusions are drawn out in the last section.

2. MEBT BETWEEN RFQ AND DTL

The MEBT in JHF/JAERI linac is required for two reasons: beam matching between RFQ and DTL; beam chopping for injection into the 3-GeV ring. For operation convenience, these two purposes should be reached in two separated sections in the MEBT, except for longitudinal matching. However, to conserve the beam quality, the line should not be too long and the beam needs to be well focused without large-amplitude envelope oscillation. The line must also leave sufficient space for the beam diagnostics.

RF-chopper is compact and has a high deflecting field [6-7]. So it is better to apply it for the 3-MeV beam in the MEBT, in comparison with the static-electric chopper, when a short MEBT is aimed. TRACE3-D was used for the beam line design. To apply this new beam-line element (RF-chopper) in the design, we modified TRACE3-D code for the inclusion of an RF-deflector (RFD) element. The fringe fields of the RF-deflector are taken into account in the modified code by reading in

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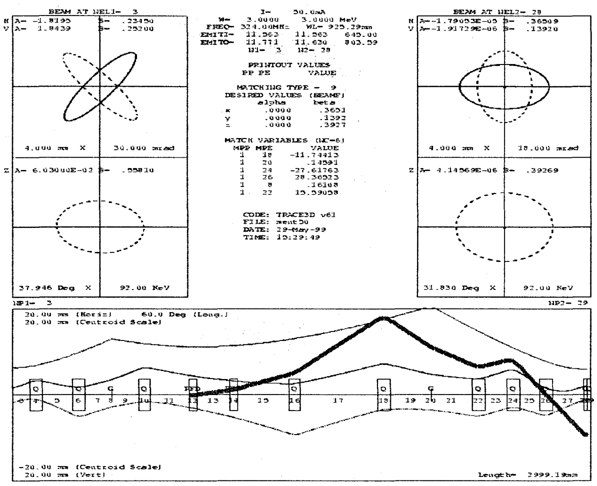
the electromagnetic field distribution from a data file generated from MAFIA run on the deflector cavity.



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V A=  1.8439   B= .25200
4.000 mm  X   30.000 mrad
Z A= 6.03000E-02 B= .55810
37.946 Deg  X  92.00 KeV

        I=     50.0mA
   W=   3.0000     3.0000 MeV
FREQ= 324.00MHz    WL= 925.29mm
EMITI=  11.563   11.563   645.00
EMITO=  11.771   11.630   803.59
        N1=  3   N2= 28

   PRINTOUT VALUES
   PP PE       VALUE

  MATCHING TYPE =  9
 DESIRED VALUES (BEAMF)
        alpha      beta
 x      .0000      .3651
 y      .0000      .1392
 z      .0000      .3927

 MATCH VARIABLES (NC=6)
  MPP MPE        VALUE
   1   18     -11.74413
   1   20        .14591
   1   24     -27.61763
   1   26      28.36523
   1    8        .16108
   1   22      15.59058

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BEAM AT NEL2- 28
H A=-1.79053E-05 B= .36509
V A=-1.91729E-06 B= .13920
4.000 mm  X   18.000 mrad
Z A= 4.14569E-06 B= .39269
31.830 Deg  X  92.00 KeV
```

Fig.2 TRACE3-D output of the MEBT. The up-left gives the input beam phase spaces and the up-right gives the matched beam with DTL. The bottom shows the beam profiles in the z, x and y directions, respectively. The dark curve traces the beam centroid offset by the two RFDs. The element sequence is denoted on the element symbol.

The output beam from the RFQ is assumed to have a normalized transverse rms emittance $\varepsilon_{x,y}$ =0.187 πmm-mrad and a longitudinal rms emittance ε_z=0.133 πMeV-degree. The MEBT design is proposed [8] with a total length of about 3 m (Fig.2). In the beam-profile plot at the bottom of the figure, the beam centroid offset in the x-direction by the two RF deflectors is depicted by the dark curve. The beam dump will be positioned at the element 18 for the chopped beam. The design procedure has two steps. At first, the beam line up-stream of the element 18 is designed aimed at the largest separation between the unchopped and chopped beams at the element 18. Then, the unchopped beam is further transferred so as to match with the acceptance of the DTL in transversal direction by the last four quadrupole magnets. Longitudinal matching is fulfilled by the two bunchers. The first buncher is also used to form a longitudinal waist in the RF-deflectors in order to obtain a sufficient deflection for the tail part of the bunch.

To verify the matched design in Fig.2, a multi-particle simulation of the 3-tank DTL was conducted. When the matched beam line is used, we see no obvious beam halos in the DTL. The rms emittance growth is also small, for instance, the longitudinal emittance growth is 1.14 times. If 99.9% particles are considered, the emittance growth becomes 1.78 times. Fig.3 shows the matched beam emittance in longitudinal direction.

However, if the elements in the MEBT have errors or the input beam into the MEBT has different Twiss parameters, the beam into the DTL becomes mismatched. To characterize the level of mismatch, a mismatch factor is used, which is defined as [3]:

$$MMF = \left[\frac{1}{2}\left(R + \sqrt{R^2 - 4}\right)\right]^{1/2} - 1 \qquad (1)$$

with R=βγ'+γβ'-2αα', here Twiss parameters with prime stand for the mismatched beam with the same phase ellipse area as the matched beam. To show the effect of the element error, we assume the gradient of the first quadrupole varies 2.6%. The resultant mismatching factors are MMFx=20%, MMFy=24% and MMFz=2% in x, y and z directions, respectively. If the input beam into the MEBT has 10% error in βz, it induces an MMFz of 5%. The same amount error in βx results in both MMFx=19% and MMFy=25%, but 2.5% in MMFz. This means the variation of the emittance shapes in the two transverse directions are coupled with each other by space-charge effect in the MEBT.

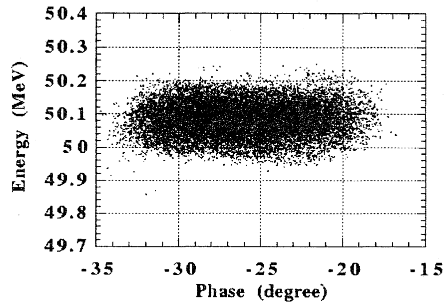

Fig.3 Longitudinal emittance of the matched beam at the exit of the DTL.

In the longitudinal direction, a voltage error of 2.5% in the second buncher can result in an MMFz=9.5% at the entrance of the DTL. As the results, a nonlinear tail is generated in the phase space plot (Fig.4), which results in an rms emittance growth of 1.18 times, and an emittance growth of 4.14 times if 99.9% particles are included.

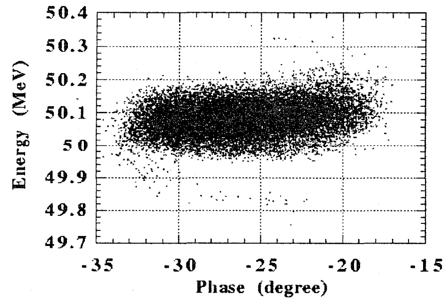

Fig. 4 Longitudinal emittance of the mismatched beam at the exit of the DTL. A long tail appears in longitudinal phase space when the input beam has a MMFz=9.5%.

3. THE BEAM LINE BETWEEN DTL AND SDTL

The RF frequency of DTL and SDTL is the same and they have a similar accelerating structure. So no beam transport line is necessary and only a drift space of one βλ is inserted between the two structures. Although the transverse focusing lattice is different between the two structures, transverse matching can be fulfilled by adjusting the last six quadrupoles in the DTL. The accelerating field in the SDTL is higher than that of the DTL. To compensate longitudinal mismatch due to the difference in accelerating gradient, the accelerating field of the SDTL needs to be tilted.

4. DESIGN OF HEBT MATCHING LINE BETWEEN SDTL AND ACS

There is an RF-frequency jump of 3 times between SDTL and ACS accelerating structures. Therefore, it is necessary to bunch and match the beam in longitudinal direction. As the beam energy is high, the beam line will be long to get enough bunching. So transverse focusing and matching are also needed.

To achieve longitudinal matching, two RF bunching tanks are applied. Frequency of 972MHz is chosen for the tanks so as to get higher bunching effect. With ten cells in each tank, the necessary bunching voltage is in a reasonable value to achieve in practice. Four quadrupole magnets are used in the beam line for transverse matching. The required magnetic field of the quadrupoles is much less than the strip limit for the H^- particle at 200 MeV. The total length of the beam line is about 5.4 m. Table 1 lists the specifications of the elements in the beam line.

Table 1 Specification of the elements in the HEBT.

Total Length	5.4 m
Q-magnet	
Number	4
Effective Length	0.2 m
B'	2.6-12 T/m
RF Tank	
Number	2
Number of cells	10
Frequency	972 MHz
E_0T	3.5, 2.5 MV/m
RF Power (P)	195 kW, 100 kW
E_0T_{max}	5 MV/m
P_{max}	400 kW

The mismatching effect is simulated with a direct input beam into the ACS without the longitudinal matching tanks. The result is plotted in Fig. 5(a). It is noticed in the beam phase space that a long tail exists and the rms emittance increases 1.61 times, while for the matched case there is almost no tail and no emittance growth, as shown in Fig. 5(b). If 99.9% beam particles are considered in the phase space, the emittance growth for the mismatched case becomes 5.24 times, but again, the matched beam still has only a very little emittance increase of 1.09 times.

5. CONCLUSIONS

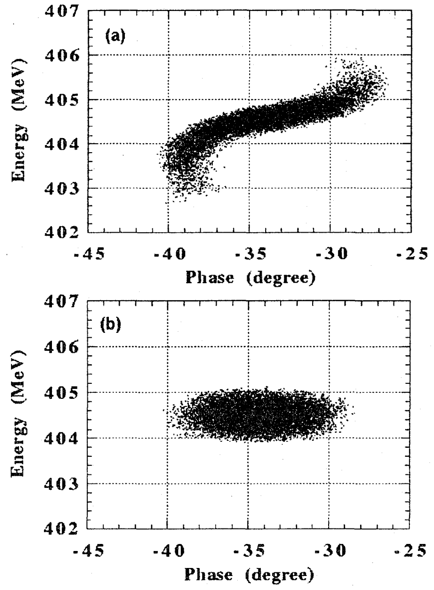

Fig. 5 Longitudinal emittance at the exit of the ACS: (a) Mismatched beam; (b) Matched beam.

The beam lines between different accelerating structures in JHF/JAERI normal conducting linac have been designed. The MEBT between the RFQ and the DTL performs both matching and chopping functions. There is no additional matching beam line between the DTL and the SDTL. Transverse matching can be achieved by adjusting the quadrupoles in the DTL and the longitudinal matching can be achieved by adopting the equal focusing strength around the transition region for both accelerating structures. HEBT uses two RF tanks with ten cells for longitudinal matching, with a beam line of 5.4 m long. Multi-particle simulations show that the matched beam has a little emittance growth. However, when a mismatching is introduced, an apparent beam halo and emittance growth happens. The results indicate how important to make the beam be matched with the accelerating structures in the JHF/JAERI intense-beam H^- linac of 50 mA peak current.

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