# DISPERSION MATCHING OF A SPACE CHARGE DOMINATED BEAM AT INJECTION INTO THE CERN PS BOOSTER

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*Abstract*

In order to match the dispersion at injection into the CERN PS Booster, the optics of the injection line was simulated using two different codes (MAD and TRACE). The simulations were benchmarked versus experimental results. The model of the line was then used to re-match the dispersion. Experimental results are presented for different optics of the line. Measurements with varying beam current show the independence of the measured quantity of space-charge effects.

## INTRODUCTION

The optics of the transfer line from the CERN proton linac (Linac 2) to the CERN PS Booster (PSB) has been subject to studies during many years [1]-[3]. While the Twiss parameters can be measured in dedicated measurement lines and empirically be adjusted to the target match, the dispersion has to be measured by changing the beam momentum and recording the displacement of the beam center. In the past, simulations and measurements of the dispersion disagreed and made a dispersion matching impossible.

After benchmarking of the simulation codes, calibration of beam line elements and debugging of the transfer line hardware, simulations and experimental data are now in excellent agreement, which leads us to the conclusion that the optics of the line is fully understood. A matched, achromatic optics has been successfully put in place and has proven to be very beneficial for the injection efficiency into the CERN PS Booster.

## OPTICS PARAMETERS

The linac-to-Booster transfer line is composed out of three parts. The first part is a straight line, which starts at the exit of the linac. It provides two measurement lines for transverse and longitudinal emittance. The beam is directed into these two measurement lines by a bending magnet, which is not used during normal operation and hence does not generate dispersion. The beam is then horizontally deflected by a bending magnet, which generates horizontal dispersion. Further downstream, a second bending magnet deflects the beam in opposite direction. The final part of the line provides two more measurement lines for transverse emittance and beam energy as well as a number of quadrupoles for the matching of the beam into the PS Booster.

The beam from the linac is a 50 MeV proton beam (311 MeV/c) with a nominal beam current of about 160-170 mA. The beam is space charge dominated at the exit of the 202 MHz Alavarez accelerator. The space charge forces diminish as the beam debunches towards the PSB.

## DISPERSION MEASUREMENT

The dispersion is measured by changing the beam momentum and observing the corresponding displacement of the beam center at all pick-ups along the line. The beam displacement is recorded for various values of momentum, averaging over three measurements for each setting. The slope of a linear fit is the required dispersion.

The change of beam momentum is accomplished by changing the phase of a debuncher cavity located 22 m downstream of the last Alvarez cavity. We have first calibrated the de-buncher in order to determine the momentum change as a function of phase. The beam momentum for different debuncher cavity phase settings was measured in a dedicated spectrometer line, where the 1 rad bending magnet is equipped with a nuclear magnetic resonance probe. The various values of the debuncher phase are applied, and the beam position at the pick-ups along the line is recorded. The dispersion is obtained off-line using a fitting routine.

## SIMULATIONS

Two independent simulation codes have been used to model the optics of the line. The code MAD [4] describes successfully the dispersion. This code does not take into account space charge. For comparison, TRACE 3-D [5] was used, which can include space charge calculation. While we will show, that the measured dispersion is a space-charge independent quantity, it is important to take into account space charge when calculating the beam envelope. The simulations presented in the following sections have hence been performed using TRACE 3-D, where for the dispersion matching the beam current has been set to zero, and for the Twiss parameter matching the beam current has been set to the nominal value of 170 mA.

Figure 1 shows a TRACE 3-D simulation of the transfer line with unmatched settings. Figure 2 shows the horizontal dispersion as calculated with TRACE 3-D for the unmatched optics and zero beam current. Horizontal dispersion starts to develop from the first bending magnet, and arrives at the second bending magnet with $D \approx 0$ but $D' \neq 0$. Consequently, $D$ and $D'$ have non-zero values throughout the rest of the line.The simulation is in excellent agreement with the experimental data.

For the case that the beam current is set to zero, TRACE 3-D and MAD give identical results. Figure 3 shows the horizontal dispersion calculated with both MAD

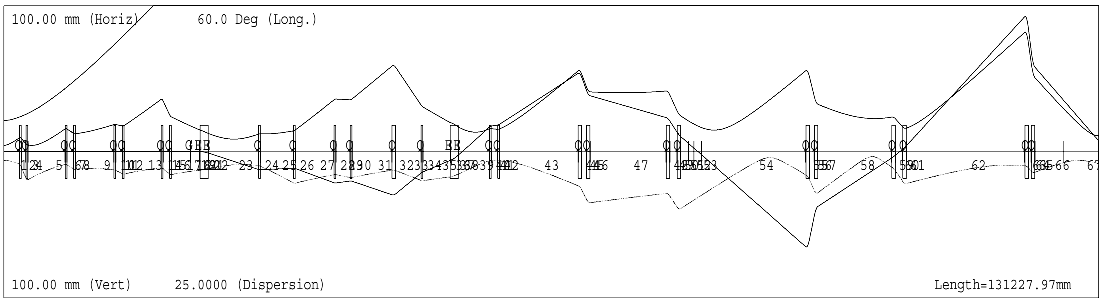


Figure 1: TRACE 3-D simulation of the line with unmatched settings. The upper and lower lines represent the horizontal and vertical envelope (scale 100 mm). The dispersion is zero in the beginning of the line and starts to develop from the first bending magnet.

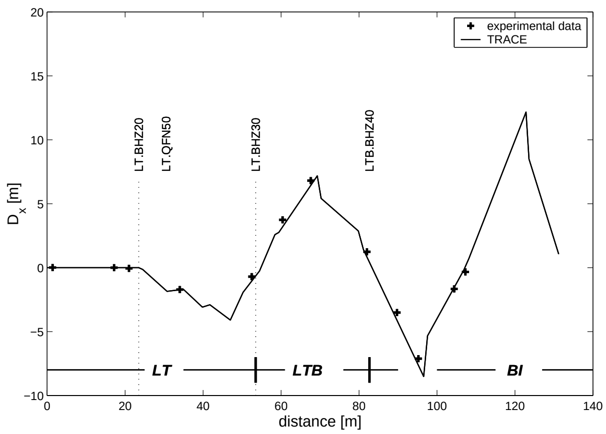


Figure 2: TRACE 3-D simulation of the horizontal dispersion along the line (solid line) and measured dispersion for the unmatched optics. The beam current in TRACE has been set to zero.

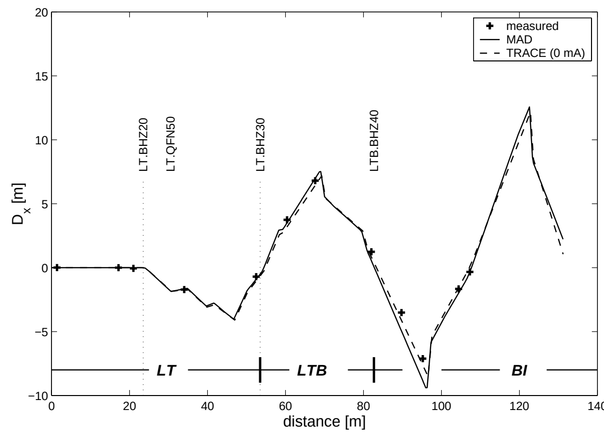


Figure 3: Dispersion along the line calculated with TRACE 3-D (dashed line) and MAD (solid line). Both codes as well as the experimental data are in good agreement.

and TRACE 3-D. Both codes agree with each other and with the experimental data. We conclude, that both codes model the line correctly. The measured dispersion is a space charge independent quantity, as only the displacement of the beam center and not the beam width is observed. However, when calculating Twiss parameters and beam envelope, space charge must be taken into account.

## SPACE CHARGE STUDIES

In order to verify experimentally the independence of the dispersion of space charge, we have reduced the beam current by changing the arc current of the proton source. Table 1 shows the beam current for three different values of the source arc current.

We have changed the beam current according to Table 1 and measured the dispersion for each setting. Figure 4 shows the measured dispersion for the different beam currents as well as a TRACE 3-D simulation with zero current. All measurements and the simulation agree. We have hence experimentally shown, that the observed quantity is space charge independent.

Table 1: Beam current as function of source arc current as used for space charge studies.

| arc current [A] | beam current [mA] |
|---|---|
| 38.45 | 170 |
| 30 | 113 |
| 20 | 60 |

## DISPERSION MATCHING

We have used the TRACE 3-D model to match both $D_x$ and $D'_x$ to zero at the exit of the second bending (LT.BHZ30). In order to match simultaneously $D_x$ and $D'_x$, the quadrupoles between the bending magnets LT.BHZ20 and LT.BHZ30 have to be used. Downstream of LT.BHZ30, the dispersion invariant cannot be changed any more and only $D_x$ be traded off against $D'_x$. If, however, both $D_x$ and $D'_x$ can be nullified (achromatic line), the dispersion function will be zero all along the rest of the line. The quadrupoles downstream of LT.BHZ30 can then be used in order to re-match the Twiss parameters at

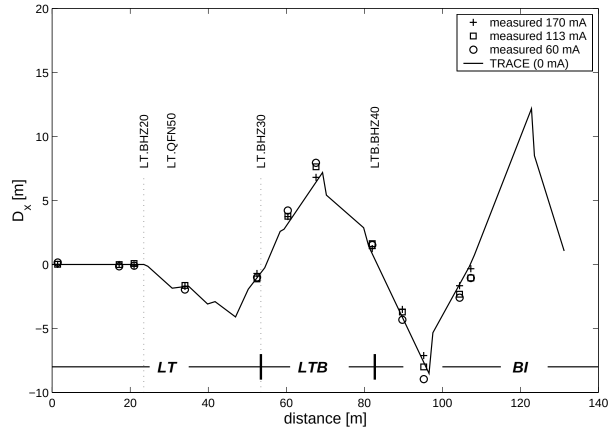


Figure 4: Measured dispersion for three different beam currents and unmatched optics. All experimental data agree with a TRACE 3-D simulation, in which the beam current has been set to zero.

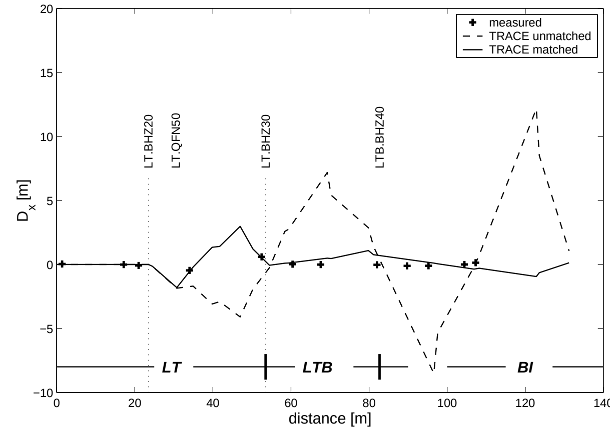


Figure 5: Horizontal dispersion calculated with TRACE 3-D along the line for achromatic optics (solid line) and unmatched optics (dashed line). For the matched optics, the dispersion changes sign between the two bending magnets and arrives at the second bend such that both $D$ and $D'$ are cancelled.

Booster injection without perturbing the dispersion matching.

Figure 5 shows the horizontal dispersion along the line for the matched case. The dispersion is zero coming from the linac, and starts to have non-zero values downstream of LT.BHZ20. The first horizontally focusing quadrupole downstream of LT.BHZ20 is used to change the sign of $D'_x$ such that $D_x$ and $D'_x$ arrive at the second bending (LT.BHZ30) with the correct sign and value such that both are cancelled. The dispersion is then close to zero downstream of LT.BHZ30. The envelope and Twiss parameters at Booster injection have been re-matched using quadrupoles downstream of LT.BHZ30. The dispersion for the unmatched optics is shown for comparison. When matching the $D_x$ and $D'_x$ using quadrupoles between LT.BHZ20 and LT.BHZ30, in general the Twiss parameter matching at Booster injection will be perturbed. The quadrupoles downstream of LT.BHZ30 have hence been used in a second iteration to re-match the Twiss parameters to the target match.

## PS BOOSTER INJECTION

The new injection line optics has dramatically improved the intensity injected into the CERN PS Booster. This can be understood from the multi-turn injection process. The beam is injected in several turns, where each beamlet undergoes several cuts at the injection septum. By reducing the horizontal beam size, less beam is lost at injection and the injection efficiency went up from 50-60% to around 75%. Furthermore, the new injection line optics has the potential to improve the brilliance of the beams, as the same number of particles can be injected with less turns and hence inside a smaller transverse emittance. This is a particularly important issue for LHC type beams.

## CONCLUSIONS

We have shown that a solution for an achromatic optics exists for the CERN PS Booster injection line. Two codes are available to model the line: MAD, which does not take into account space-charge, and TRACE 3-D, which allows space-charge calculation. We have experimentally shown, that the dispersion is a space-charge independent quantity. The matched optics has proven to be beneficial for the PS Booster injection efficiency.

## REFERENCES

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[4] MAD Version 8.23/08 Linux.

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