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MAD and *BeamOptics* Description of the `TT2/TT10` Transfer Lines Part I: Optics without Emittance Exchange Insertion

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Abstract

A set of reference files was created to model the beam optics of the `TT2/TT10` transfer lines using the program packages *MAD* and *BeamOptics*. The geometry of the model has been cross checked versus the *CERN* official survey data. The structure of the files and the notation are explained and the reference files presented.

Geneva, Switzerland
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1 Introduction

In recent years, there has been a renewed interest in the study of the transfer line TT2/TT10 to minimise the emittance blow-up at injection into the SPS for two main reasons:

- to minimise the losses for the high intensity fixed target proton and lead ion beams which have vertical emittances comparable to the physical vertical acceptance of the SPS machine.
- to fulfil the brilliance requirements for the LHC beam to achieve goal luminosity.

In both cases, the success of the physics runs relies on the overall performance of the accelerator chain and transfer lines. In particular, the optics of the transfer line should be computed in order to match the circular machines. In practice, one should also be able to do fine tuning the line to compensate the unavoidable discrepancy between the model and the reality.

For these reasons, a special effort has been put to define an optical model of the TT2/TT10 transfer line to be used both for the theoretical studies and the parameter-tuning during the routine operation (for instance, in the conjunction with *ABS*-like applications [1]). A *MAD* [2] model was already available since the early 90s [3]. Since then a number of modifications on the hardware installed have been carried out. Hence, it has been decided to update, cross-check and possibly improve the structure of the available files thus providing the users' community a set of *official files* which should be used for the optical analysis of the TT2/TT10 transfer line.

Furthermore, in recent years, new simulation programs have been proposed to the attention of the accelerator physics community. Among them, *BeamOptics* [4] represents a new generation of tools based on symbolic computation. The capability of carrying out symbolic computations is based on the *Mathematica* package [5]. To exploit the power of this new approach a set of input files, describing the TT2/TT10 transfer line using the *BeamOptics* syntax, have been provided in addition to the *MAD* model.

This note describes the structure of the files used to build up the two models *MAD* and *BeamOptics*. It also gives some details on the reference optics used at 26 GeV/c for the LHC beam and it provides the information needed to access the data on the afs file system.

2 *MAD* Notation and File Structure

The *MAD* program [2] requires essentially three different types of input: definition of beam line elements, element sequence and element setting. Element definitions and sequence are given by the hardware; these files should not be modified, except when a change in the hardware installed occurs (as it was the case during the 1997/98 shut-down. See Ref. [6] for more details). The magnetic setting defining the beam line optics is the only parameter that should be varied by the user.

The set of *MAD* files is therefore built up strictly modular. It consists of element definition files, sequence files and strength files. In addition to these basic constituents, there are more files which contain command lines for computation, matching, plotting as well as additional information e.g. on misalignments. The modules must be called from a run file in the correct order.

2.1 Element Definition

The definition of magnetic elements for a beam line is given in the file `filename.ele`, where `filename` is in general the name of the beam line, e.g. `tt2.ele`. The element definition file contains the names of all beam line elements, the element type and geometric parameters such as length, angle and tilt. The angles given in the `*.ele` files are nominal angles. If additional trims are added, they are specified in the `*.str` file. For this purpose *virtual elements*, in the form of zero-length dipole kicks, are included in the `*.seq` file. They are placed

at the entrance of the bending magnets whose deflection angle is adjusted. This is imposed by the properties of the bending magnets as defined by the *MAD* program: a change in the bending angle modifies the reference geometry of the line. Hence all the subsequent elements (quadrupoles, for instance), are always centered with respect to the beam trajectory and this is not the case in reality. On the other hand, a dipole kick does not modify the reference trajectory and it is possible to reproduce the effects due to an off-axis passage through the quadrupoles.
Besides the definition of single elements, the definition file can also introduce element types, i.e. element families with identical physical properties. For quadrupoles, it contains the length and the family type, an example would be

```
QFO165 : QUADR, L= 1.2000, TYPE=FL
```

For the `TT2/TT10` transfer lines, the definition files `tt2.ele` and `tt10.ele` were created.

2.2 Element Sequence

To create a beam line out of a given set of elements, *MAD* provides two different commands, namely the `beamline` and `sequence` syntax. For the `TT2/TT10` reference files, the `sequence` type was chosen since it is more flexible for future modification. The notation is `filename.seq` where `filename` is consistent with the corresponding `*.ele`.

For the `TT2` and `TT10` transfer lines, individual sequence files were created. The filenames are `tt2.seq`, `tt10.seq`. As the `TT2` beam line is connected to other transfer lines (`FTA, TTL2, FT12`) a decision has been taken to split it up into four parts called `TT2A, TT2B, TT2C, TT2D` defined as follows

- `TT2A`: From the entrance of the quadrupole `QFO105` up to the exit of the bending `BTI248`.
- `TT2B`: From the exit of the bending `BTI248` up to the exit of the bending `BHZ327`.
- `TT2C`: From the exit of the bending `BHZ327` up to the entry of the bending `BHZ377`
- `TT2D`: From the entry of the bending `BHZ377` up to the `D3` dump.

Using this modular structure, its possible not only to model the `TT2/TT10` line, but also, in the near future, the other lines `TT2/FTA`, `TT2/TTL2` and `TT2/FT12`.
In addition to the standard files defining the nominal element positions, misalignment files `tt2.mis, tt10.mis` are provided which may be called after the sequence file.

2.3 Element Setting

The element setting file must be called after the definition file. It contains the quadrupole setting in terms of K_1 values[1)]. The notation is `filename.str`; once again `filename` corresponds to the name of the beam line. Since the strength file contains only the setting and not the physical properties of the elements, it is the only file that should be varied by the user. The following set of reference strength files is provided:

- `tt2_fe_26_k.str`: matched `TT2` strength file for 26 GeV/c proton beam, fast extraction from `PS`, no emittance exchange insertion.
- `tt10_fe_26_k.str`: matched `TT10` strength file for 26 GeV/c proton beam, fast extraction from `PS`, no emittance exchange insertion.

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1) A second set of files, where the quadrupole setting is given in terms of currents, is provided. The files are called `tt2_fe_26_i.str, tt10_fe_26_i.str`.

Further files are in preparation for the 14 GeV/c proton beam including the emittance exchange insertion in the `TT10` line. Since this special insertion cannot be handled by *MAD* in a straightforward way[2)] by using the standard sequence file, the details of the sophisticated treatment needed will be reported elsewhere.

2.4 Action Files

While a given beam line is created from `*.ele`, `*.str` and `*.seq` files, the computation of beam optics in the transfer line requires a set of initial conditions for the optical parameters together with an execution command. Those parameters are provided as reference files: The initial conditions are given in input files called `*.inp`. Two input files are provided:

- `tt2.inp` gives the nominal initial conditions of the optical parameters α, β, D, D' and beam trajectory at the entry of `TT2` for the 26 GeV/c proton beam without emittance exchange insertion.
- `tt10.inp` gives the nominal initial conditions α, β, D, D' at the entry of `TT10` for the 26 GeV/c proton beam without emittance exchange insertion.

The computation of the *Twiss* parameters is carried out by calling the `twiss.cmd` file, for the case without linear coupling, or `twiss_c.cmd` for the case where linear coupling is present.

The description of a beam line together with initial conditions for the optical parameters and `twiss` command are the minimum set of ingredients to compute the beam optics of a given beam line. Additional files executing *MAD* commands such as `plot`, `survey`, `match` can be called or the commands can be directly executed in the run file. Two additional files are available `tt2.sur, tt10.sur` to compute the beam line geometry and a third file `plot.cmd` is created to plot the fundamental optical functions.

2.5 Run File

The run file is essentially a series of *MAD* `call` commands used to read-in the input files `*.ele`, `*.seq`, `*.str`, followed by the initial conditions contained in the `*.inp` file and the `twiss` command. The convention used for such a file is `filename.mad`. A general pattern of a run file is given in Appendix A.

3 Cross Check versus Survey Data

The first step in the verification of the optical model consists in checking the geometry. *MAD* allows to compute the geometry of a generic beam line by using the `survey` command. Furthermore, it is possible to retrieve the official data concerning the measured geometry of the real beam line. At *CERN* these data are archived in the *Geode* database [7].

The `TT2` and `TT10` sequence files were cross checked versus the *Geode* data. The coordinates of the magnet entry, as computed by *MAD*, are compared with the measured positions. The difference between the two sets of data was calculated for the three axes x, y and z. In Fig. 1 is shown such a difference for `TT2` all along the transfer line. In the horizontal plane, the agreement is excellent, apart from the final part of `TT2`. This discrepancy can be easily explained: an horizontal dipole was dismantled some years ago. It is still included in the database but not in the *MAD* model, thus producing the discrepancy. In the vertical direction, one can clearly see a discrepancy which builds up to 7 mm at the end of `TT2`. This is an effect of the earth curvature. In reality the beam line is flat and so is the *MAD* model (obviously!). However, the survey data are not treated in such a way to subtract this effect.

[2)] The E. D. Teng formalism used in *MAD* is valid for circular machines only.

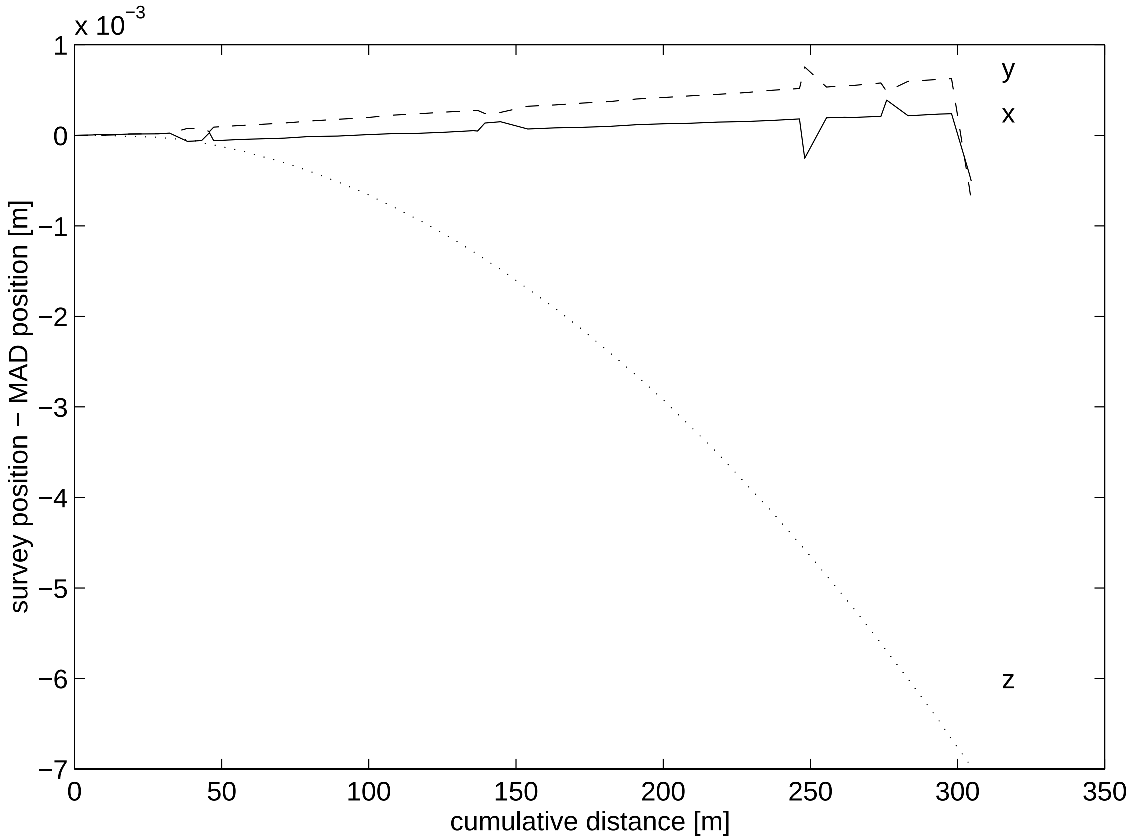

Figure 1: Difference between the *MAD* survey output and *CERN* survey data for the `TT2` transfer line. A discrepancy of about 7 mm builds up in the vertical direction due to earth curvature effect. The discrepancy in the horizontal plane at the end of `TT2` is due to an horizontal dipole which has been dismantled in reality but is still present in the *Geode* database.

In Fig. 2 is shown the result of a similar comparison between *MAD* and *Geode* for the `TT10` line. In this case the agreement is excellent along the three directions. The different treatment of the survey data with respect to the one performed for the `TT2` line [8] allows to subtract the earth curvature effect. The 1 mm difference at the end of the `TT10` beam line is linked with the finite precision used for the initial conditions.

4 *MAD* Results

The transfer line optics was computed using the *MAD* files given in the previous sections. The misalignment of the magnetic elements are not taken into account in this case. Figure 3 shows the horizontal and vertical β-function along the transfer line, Fig. 4 shows the horizontal and vertical α-function and Fig. 5 shows the horizontal and vertical phase advance μ for the `TT2/TT10` line. Finally, in Fig. 6 is shown the dispersion function, horizontal and vertical, for the whole line. The plots are produced using the element settings for the 26 GeV/c `LHC` beam as used in 1997.

5 *BeamOptics* Notation and File Structure

The modelling of the `TT2` and `TT10` lines using *BeamOptics* is based on an existing set of *MAD* input files describing the magnetic lattice. By using the *MAD* command `structure` (see Ref. [2] for more details) it is possible to generate a file which contains the necessary

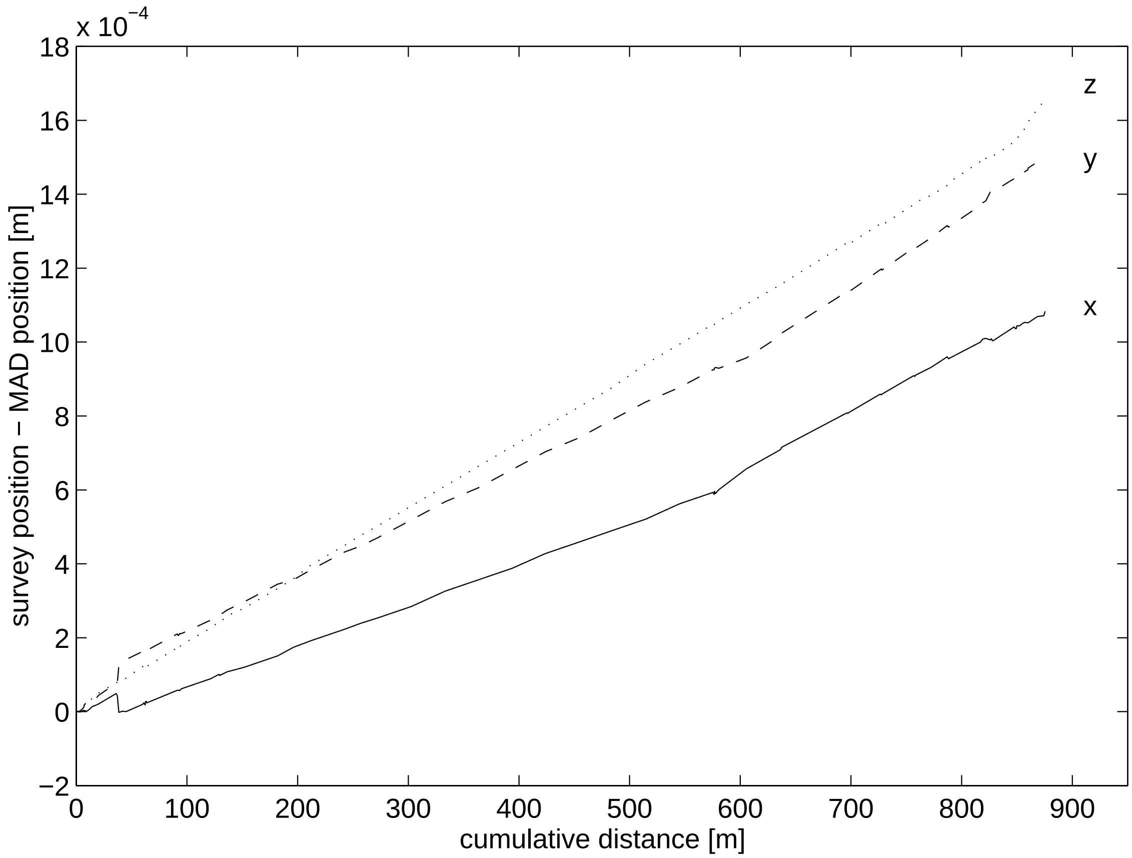

Figure 2: Difference between the *MAD* survey output and *CERN* survey data for the `TT10` transfer line. A discrepancy of about 1 mm builds up in the three directions due to a slight discrepancy in the initial conditions.

information for *BeamOptics*. Furthermore, the structure file has a format which can be easily interpreted by *Mathematica*. This file contains a two lines header record followed by a set of element records, each of them beginning with the element keyword (`DRIF` for a drift, `QUAD` for a quadrupole, `SBEN` or `RBEN` for a bending magnet, `SEXT` for a sextupole, `OCTU` for an octupole, etc.), the name of the element and its length. The remaining information depends upon the element type. For linear magnets, the values are the deflection angle, the normalised focusing strength and its first derivative, the roll angle about the longitudinal axis, the rotation angle for the entrance and exit pole face and the curvature of the entrance and exit pole face:

`symbol name L [m] ANGLE [rad]` K_1 `[`m^{-2}`]` K_2 `[`m^{-3}`] TILT [rad]`
E_1 `[rad]` E_2 `[rad] H1 [`m^{-1}`] H2 [`m^{-1}`]`

For thin multipoles the record contains the keyword (`MULT`), its name, the length (zero), the horizontal and vertical deflections, the highest order written and the multipole components (normal and skewed).

The conversion of the *MAD* structure file to BeamOptics is performed by translating the data prepared by the command `structure` into a *Mathematica* list using the `ReadList` command and formating the data in a table with as many rows as elements and as many columns as parameters (discarding thin multipoles). Each record is composed at present of 10 data fields, namely, the element name, its keyword (`SS` for a drift, `Q` for a quadrupole and `Bend` for a bending magnet), the length of the curved trajectory, the deflection angle, the normalised focusing strength and its first and second derivatives, the angles of the normal to the upstream and downstream faces with the reference trajectory and the roll angle about the longitudinal axis:

name symbol L [m] ANGLE [rad] K_1 [m^{-2}] K_2 [m^{-3}] K_3 [m^{-4}]
E_1 [rad] E_2 [rad] TILT [rad]

The resulting *Mathematica* list is further transformed into a lattice structure with the *BeamOptics* command `ToChannel` which converts the data table into a beam line whose arguments are drift spaces and magnetic elements. This yields the optical description of the horizontal plane. Conversion to the vertical plane was carried out using the operator `ToVertical`. Once the conversion of the lattice data from *MAD* to *BeamOptics* format is carried out, the process for computing the optical parameters can be started.

Given the initial conditions $\beta_{H,V}$, $\alpha_{H,V}$, $D_{H,V}$, $D'_{H,V}$ and $\mu_{H,V}$ at the `TT2` input, the optical parameters may be traced in both planes at the input of each element by using the *BeamOptics* commands `SigmaAll`, `DvectorAll` and `MuAll`. Similarly, plots of betatron, phase advance and dispersion functions are performed by means of `BetaPlot`, `DPlot` and `MuPlot` commands. The optical parameters have been calculated by *BeamOptics* at the same locations as those obtained by *MAD*, using the commands `SigmaAt`, `DvectorAt` and `MuAt`. All these commands have been prepared and included in a *Mathematica Notebook* named `tt2tt10.nb`. Although such a *Notebook* has been prepared for the `TT2/TT10` beam line, it can be used to convert a generic beam line described using the *MAD* syntax into a *BeamOptics* description.

6 *BeamOptics* Results

The transfer line optics was computed using the *MAD* structure file and the *Mathematica Notebook* described in the previous section. Figure 7 shows the horizontal and vertical β-function along the transfer line, Fig. 8 shows the horizontal and vertical α-function and Fig. 9 shows the horizontal and vertical phase advance μ for the `TT2/TT10` line. Finally, in Fig. 10 is shown the dispersion function, horizontal and vertical, for the whole line. The plots are similar to those produced with *MAD*.

7 Outlook

While the sequence files for `TT2` and `TT10` should remain unchanged unless hardware components are added or removed, the element setting is flexible. The strength files provided so far refer to the matching done in 1997 [10] for the 26 GeV/c proton beam, fast extraction, without emittance exchange insertion. In case the optics of the transfer lines will be re-matched, the new settings will be provided as new strength files.

Another set of files will be provided for the 14 GeV/c Continuous Transfer (CT) beam used for fixed target operation. The files will follow the same notation.

Acknowledgements

The authors would like to thank T. Dobers, F. C. Iselin, J.-P. Quesnel and J. Ramillon for helpful discussions.

References

[1] B. Autin, V. Ducas, A. Lombardi, M. Martini, E. Wildner, Automated Beam Optics Correction for Emittance Preservation, *Part. Accel.* **58**, (221) 1997.

[2] H. Grote, F. C. Iselin, The *MAD* Program, User's Reference Manual, *CERN SL (AP)* **90-13** (1990).

[3] T. Risselada, Beam Optics Data for the PS Ring and its Transfer Lines, *CERN PS Note (PA)* **92-04** (1992).
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[5] S. Wolfram, Mathematica, a system for doing mathematics by computer, (Addison-Wesley, NY, 1993).
[6] J-Y. Hémery, Additional vertical corrector in the PS to SPS transfer line (TT2/TT10), *CERN PS Note (CA)* **98-03** (1998).
[7] J. Gervaise, M. Mayoud, E. Menant, Système tridimensionel de Coordonées utilisé au CERN, *CERN* **76-03** (1976).
[8] J-P. Quesnel, private communication, 1998.
[9] M. Martini, E. Métral, Comparison between *BeamOptics* and *MAD* Modellings: Application to the PS Ring and TT2 Transfer Line, *CERN PS Note (CA)* **98-06** (1998).
[10] G. Arduini, private communication, 1998.

A *MAD* Reference Files

The *MAD* reference files are accessible under the `afs` file system. At the following address

`/afs/cern.ch/group/pz/cps/TransLines`

we have built-up a tree-structure where the files concerning the various transfer lines of the PS Complex can be found. The description of the various sub-directories is given in the following:

`/Lib`: it contains general purpose files, like *MAD* files used to compute *Twiss* parameters and to plot optical functions.

`/PSB-PS`: It contains the model of the transfer lines from PSBooster to PS. It is empty at the moment.

`/PS-AD`: It contains the model of the transfer lines from PS to AD. It contains the FTA line model.

`/PS-SPS`: It contains the *MAD* model described in this note of the TT2/TT10 transfer line.

These files can be called within a *MAD* command file or copied to a private directory for further use. We give here an example for a run file which calls the different modules:

```
!---------------------------------------------------------------------------
! MAD file for TT2/TT10 optics calculations
! K.Hanke & M.Giovannozzi 1998, original version by G.Arduini
!---------------------------------------------------------------------------
title, 'TT2/TT10 optics - no Emittance Exchange Section - 26 GeV'
option, -echo
option, -double
system, 'rm -f p'
system, 'rm -f l'
system, 'ln -s /afs/cern.ch/group/pz/cps/TransLines/PS-SPS p'
system, 'ln -s /afs/cern.ch/group/pz/cps/TransLines/Lib l'
!---------------------------------------------------------------------------
! call the element definition and strength file for TT2
!---------------------------------------------------------------------------
call, filename = 'p/tt2.ele'
!--------------------------------------------strength file based on K values
!call, filename = 'p/tt2_fe_26_k.str'
!--------------------------------------------strength file based on I values
call, filename = 'p/tt2_fe_26_i.str'
!---------------------------------------------------------------------------
! call the sequence file for TT2
!---------------------------------------------------------------------------
call, filename = 'p/tt2.seq'
!---------------------------------------------------------------------------
! call the misalignment file for TT2
!---------------------------------------------------------------------------
!call, filename = 'p/tt2.mis'
!---------------------------------------------------------------------------
! call the element definition file for SPS (needed for TT10)
!---------------------------------------------------------------------------
call, filename = 'p/sps.ele'
```

```
call, filename = 'p/sps.str'
!-----------------------------------------------------------------------------
! call the element definition and strength file for TT10
!-----------------------------------------------------------------------------
call, filename = 'p/tt10.ele'
!-------------------------------------------strength file based on K values
!call, filename = 'p/tt10_fe_26_k.str'
!-------------------------------------------strength file based on I values
call, filename = 'p/tt10_fe_26_i.str'
!-----------------------------------------------------------------------------
! call the sequence file for TT10
!-----------------------------------------------------------------------------
call, filename = 'p/tt10.seq'
!-----------------------------------------------------------------------------
! call the misalignment file for TT10
!-----------------------------------------------------------------------------
!call, filename = 'p/tt10.mis'
!-----------------------------------------------------------------------------
! set initial twiss parameters
!-----------------------------------------------------------------------------
call, filename = 'p/tt2.inp'
!call, filename = 'p/tt10.inp'
!-----------------------------------------------------------------------------
! build up the geometry of the beam lines and select a line
!-----------------------------------------------------------------------------
!tt2 : line = (tt2a, tt2b, tt2c) ; use, tt2
!tt2d3 : line = (tt2a, tt2b, tt2c, tt2d); use, tt2d3
! use, tt10
tt2tt10: line = (tt2a, tt2b, tt2c, tt10); use, tt2tt10
!-----------------------------------------------------------------------------
! call the action file
!------------------------------------------------------------survey of TT2
call, filename = 'p/tt2.sur'
!------------------------------------------------------------survey of TT10
!call, filename = 'p/tt10.sur'
!-----------------------------------------------twiss if no linear coupling
!call, filename = 'l/twiss.cmd'
!-----------------------------------------------twiss if linear coupling
!call, filename = 'l/twiss_c.cmd'
!--------------------------------------------------------plot Betas + Disp
!call, filename = 'l/plot.cmd'
stop
```

B *BeamOptics* Reference Files

The *BeamOptics Notebook tt2tt10.nb* is accessible under the `afs` file system, at the following address

`/afs/cern.ch/group/pz/cps/TransLines/Lib`

By simply modifying the path and name of the *MAD* `structure` file specified inside the *Notebook*, one can generate a *BeamOptics* description of a generic transfer line.

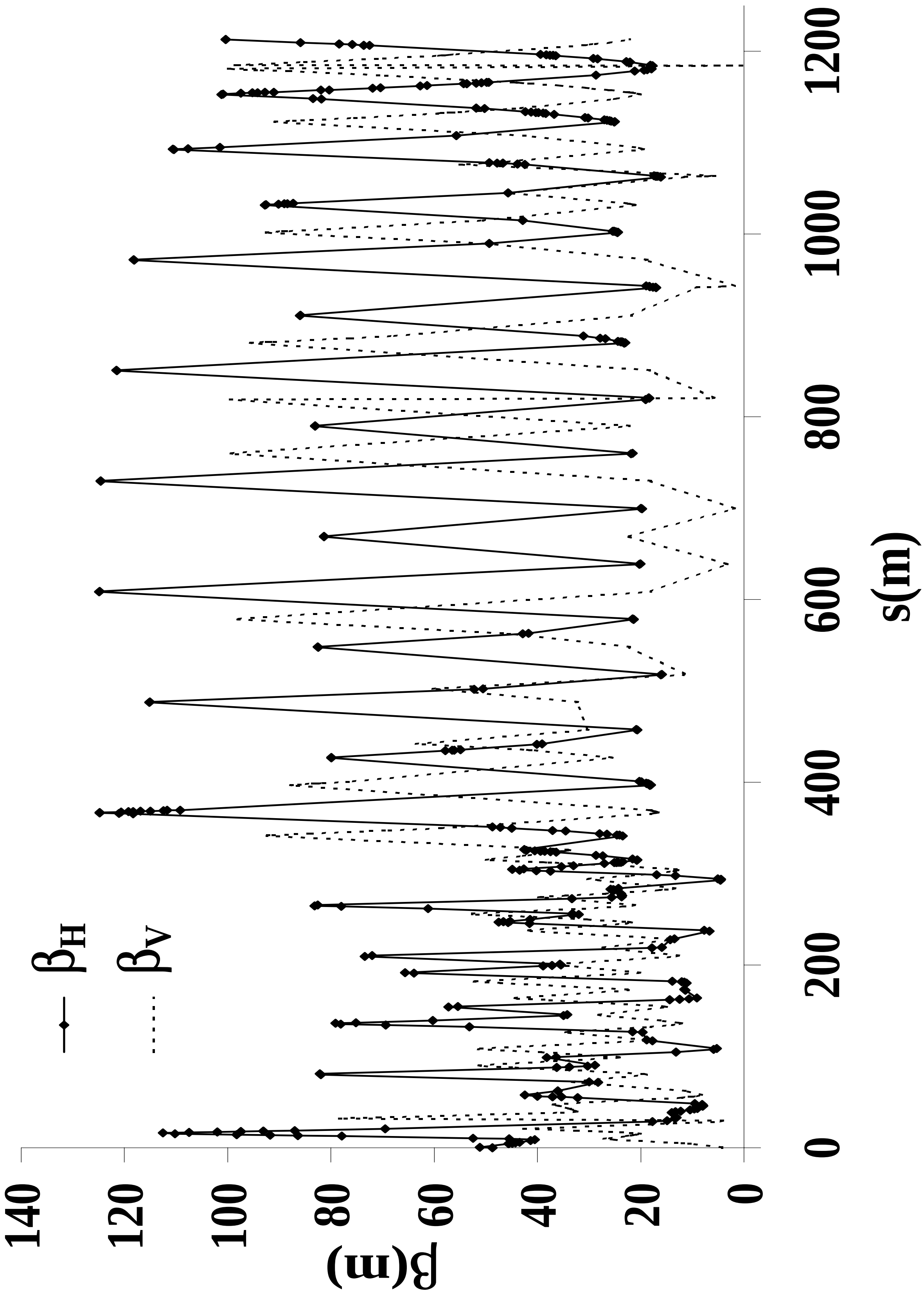

Figure 3: Horizontal and vertical β-functions for the `TT2` and `TT10` lines as computed by *MAD*.

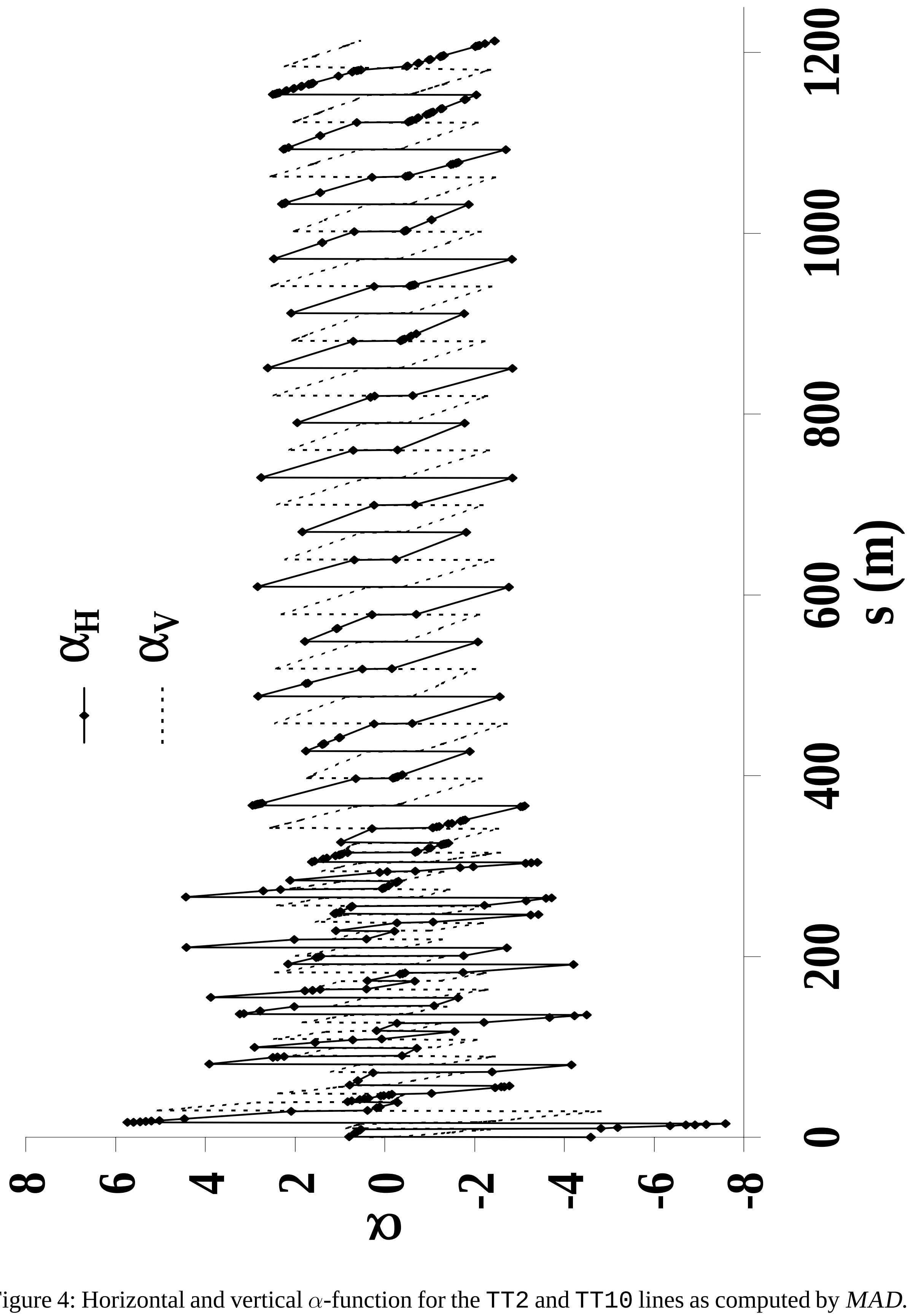

Figure 4: Horizontal and vertical α-function for the `TT2` and `TT10` lines as computed by *MAD*.

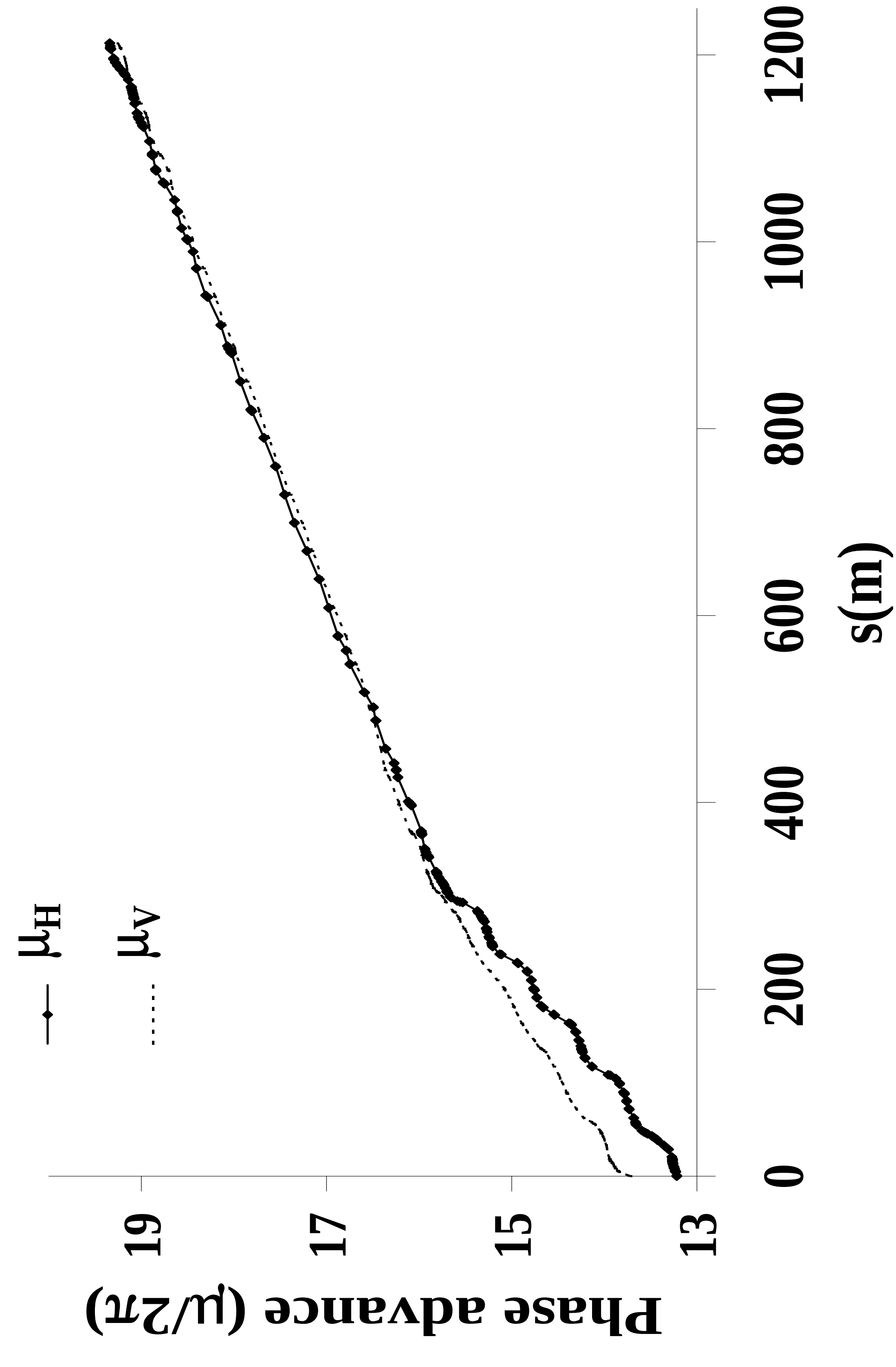

Figure 5: Horizontal and vertical phase advance for the `TT2` and `TT10` lines as computed by *MAD*.

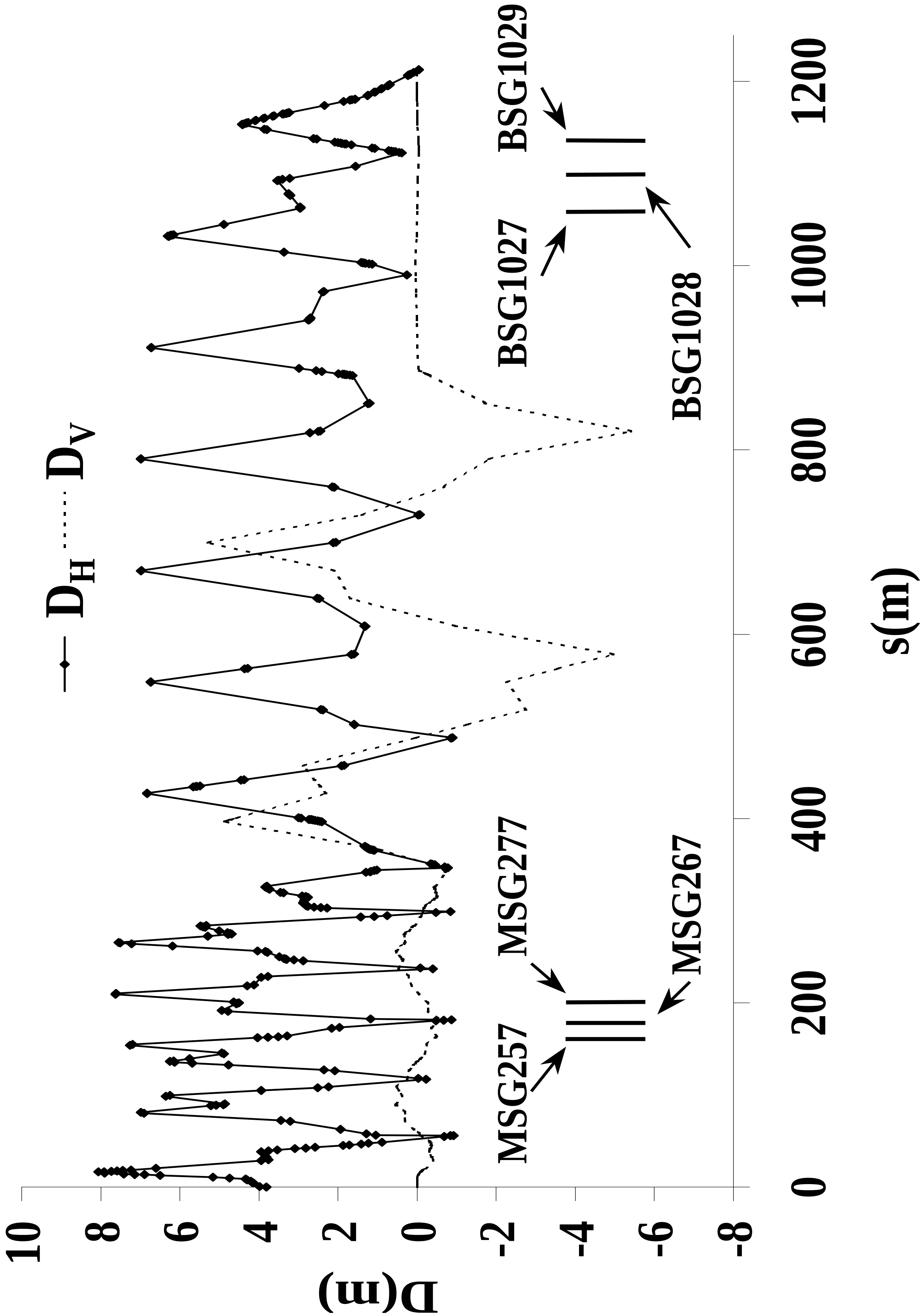

Figure 6: Horizontal and vertical dispersion function for the TT2 and TT10 lines as computed by *MAD*. The position of the beam profile monitors installed in the lines is also shown.

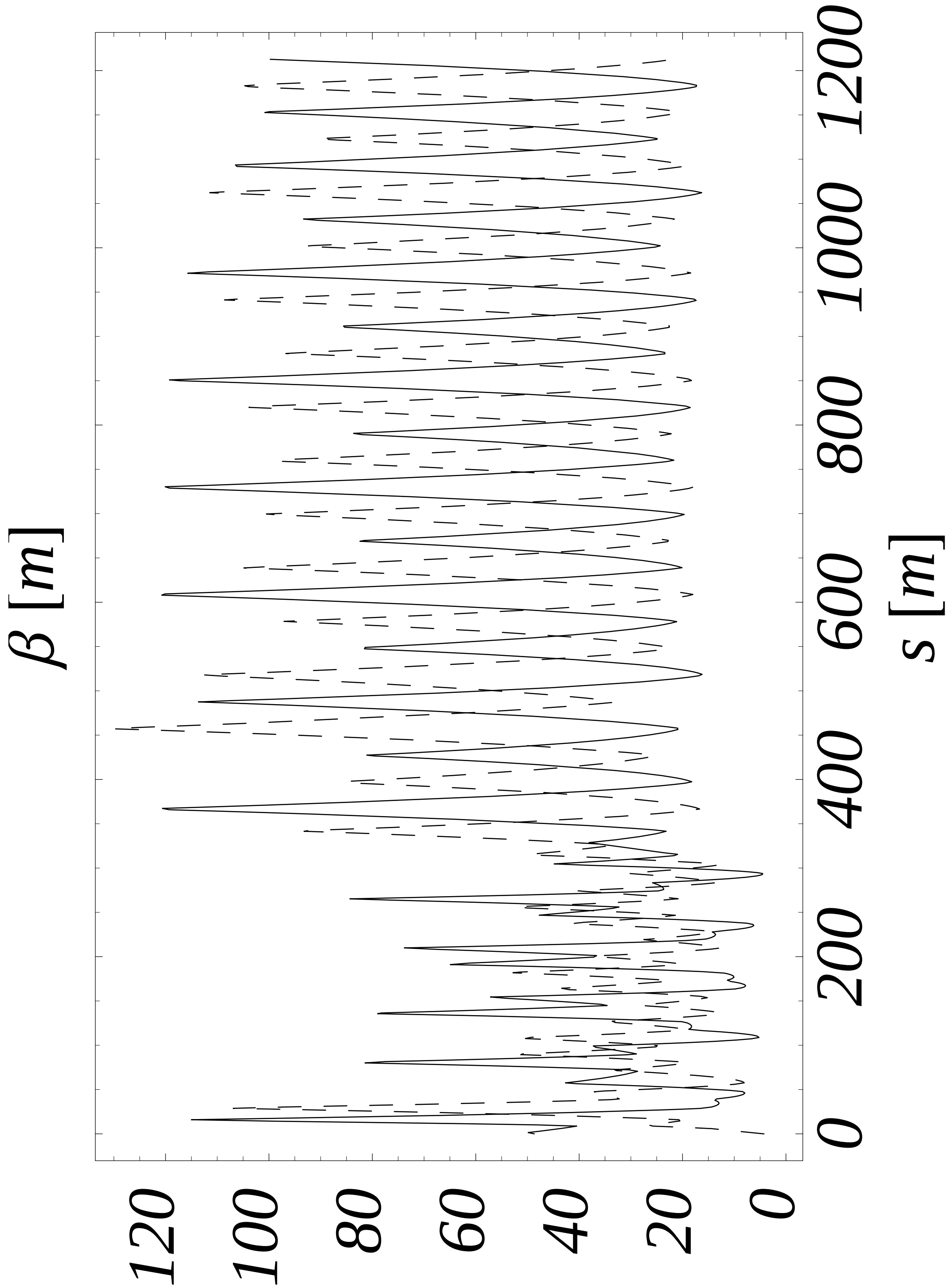

Figure 7: Horizontal and vertical β-functions for the `TT2` and `TT10` lines as computed by *BeamOptics*.

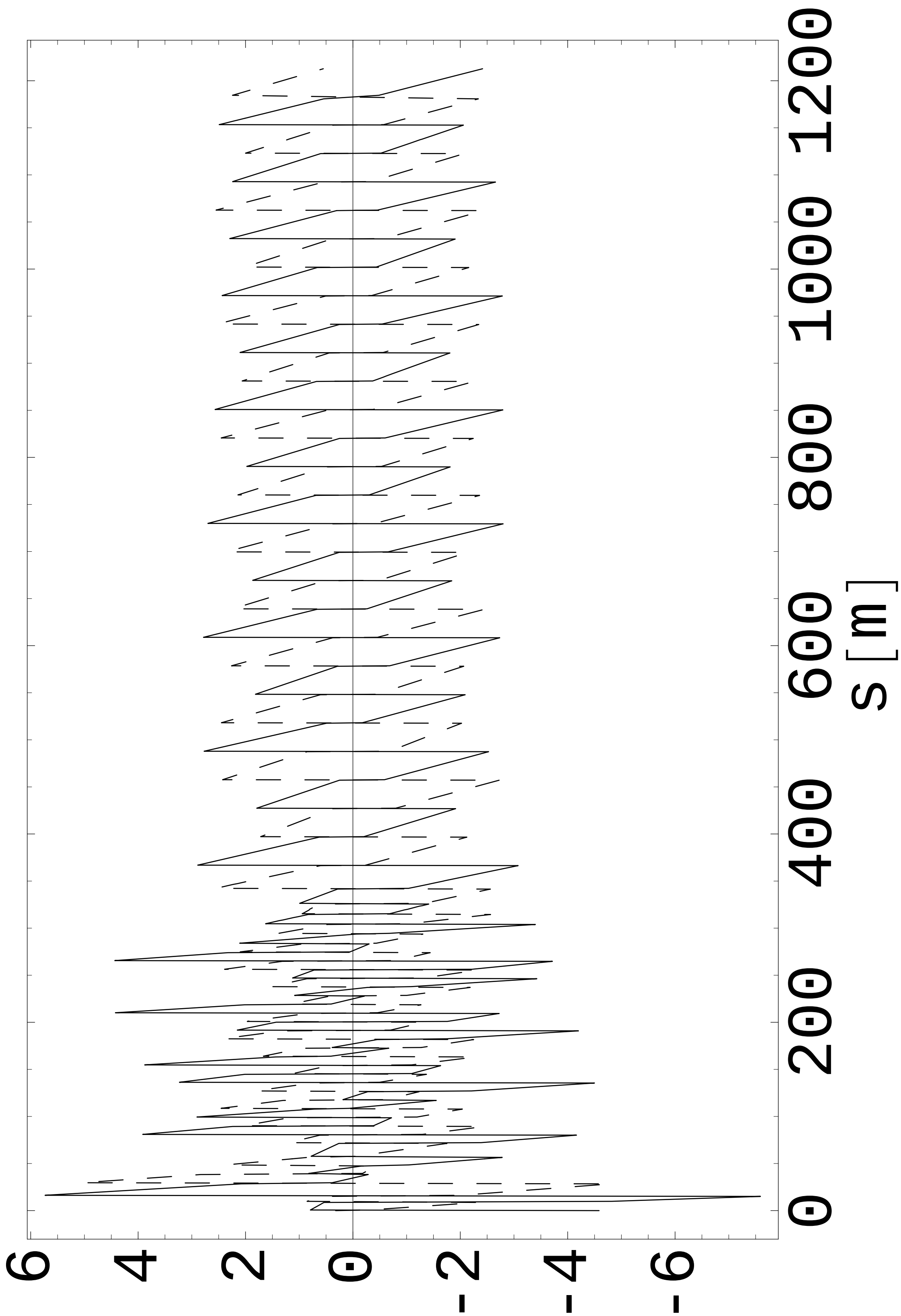

Figure 8: Horizontal and vertical α-function for the `TT2` and `TT10` lines as computed by *BeamOptics*.

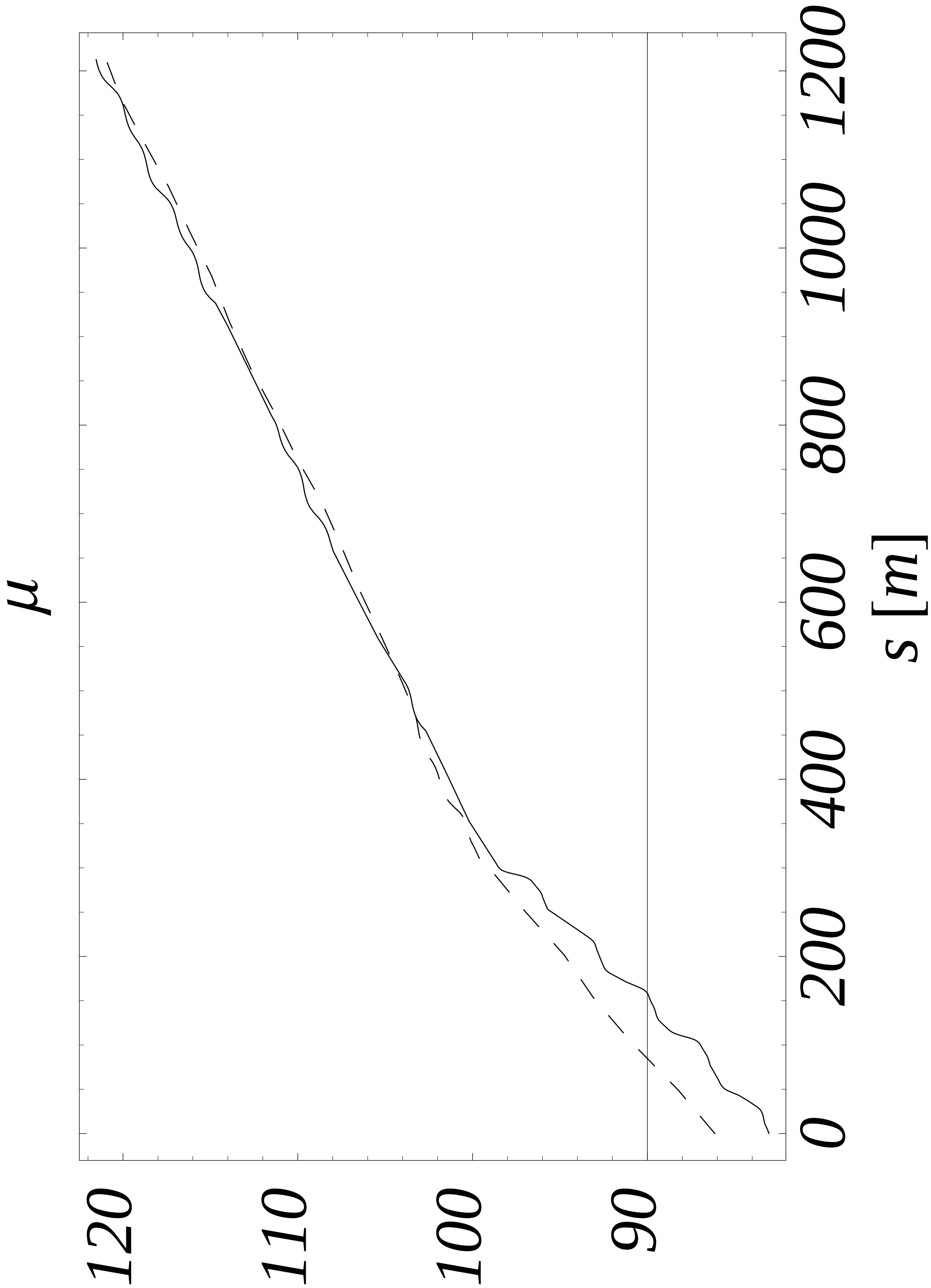

Figure 9: Horizontal and vertical phase advance for the `TT2` and `TT10` lines as computed by *BeamOptics*.

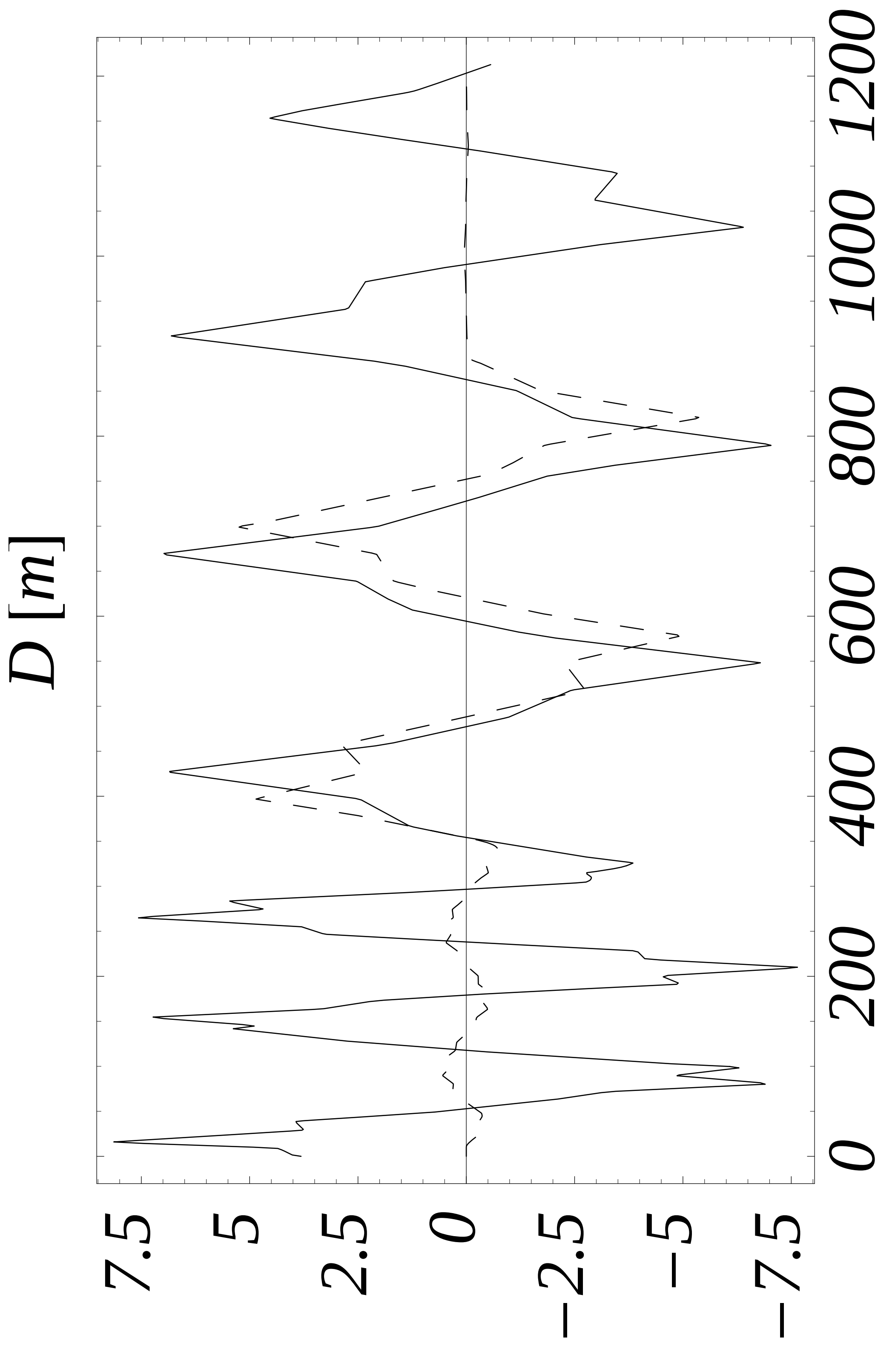

Figure 10: Horizontal and vertical dispersion function for the `TT2` and `TT10` lines as computed by *BeamOptics*.

Distribution List

G. Arduini	SL/OP
M. Arruat	PS/CO
B. Autin	PS/DI
J. Boillot	PS/OP
R. Cappi	PS/CA
C. Carli	PS/CA
D. Dumollard	PS/CA
T. Eriksson	Ps/OP
M. Giovannozzi	PS/CA
M. Gourber-Pace	PS/OP
K. Hanke	SL/OP
J-Y. Hémery	PS/CA
H. Hilaire	SL/BT
A. Jansson	PS/OP
O. Jensen	PS/OP
P. Knaus	PS/OP
M. Lindroos	PS/OP
A. Lombardi	PS/HP
D. Manglunki	PS/CA
M. Martini	PS/CA
E. Métral	PS/CA
G. Métral	PS/OP
J-P. Riunaud	PS/CA
K. Shindl	PS/DI
J. Schinzel	EST/ISS
O. Tungesvik	PS/OP
J. Uythoven	SL/OP