

Introduction to MAD-X

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Inspired by W. Herr's material

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THE MAD-X LECTURES

We will have

- ▶ **1 h lecture** (now).
- ▶ **6 h "hand-on" tutorials during the week.**
 - ▶ Today's tutorials (2×1 h) will be dedicated to get familiar with the MADX environment, to prepare a very simple input file and to explore a simple lattice cell.
 - ▶ Tomorrow's tutorials (2×1 h) will be devoted to the FODO lattice and transfer lines.
 - ▶ On Friday's tutorials (2×1 h) we will play with chromaticity and the LHC lattice.

Each tutorial is split in two parts of ≈ 20 min each (last 20 minutes for Q&A). Basic knowledge of Linux is assumed but do not hesitate to ask in case: **we (Andrea, Guido, Hector and Nuria) are here to help.**

MAD-X IN <60M:00s!

Introduction

MAD-X syntax

“Hello World!” example

DISCLAIMER. This material is intended to be an introduction to MAD-X: a large part of the code capabilities are not discussed in details or are not discussed at all! **We will use MAD-X to “visualise” the transverse dynamics concepts. The main goal here is to help you to be exposed to the beam dynamics from a new perspective.**

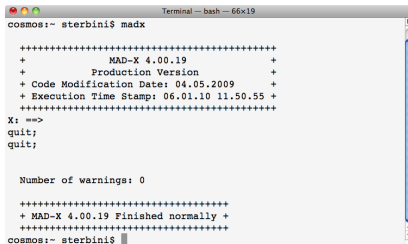
If you want to deepen the subject you can find a lot of material on the web (i.e., here¹)...

- ▶ googling “**madx**”, you get the MAD-X homepage.
- ▶ To wet your appetite, you can google “MAD-X primer”.
- ▶ To go in details, you can google “MAD-X manual”.

¹<http://madx.web.cern.ch/madx/releases/last-rel/madxguide.pdf>

WHAT IS MAD-X?

- ▶ A general purpose beam optics and lattice program distributed for free by CERN.
- ▶ It is used at CERN since more than 25 years for machine design and simulation (PS, SPS, LHC, linacs...).
- ▶ MAD-X is written in C/C++/Fortran77/Fortran90 (source code is available under CERN copyright).

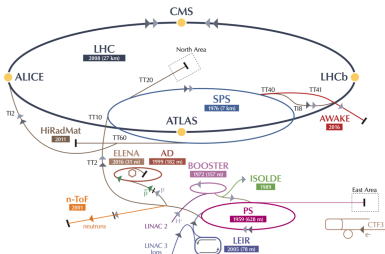


```
Terminal -- bash -- 66x19
cosmos:~ sterbini$ madx
+++++
+ MAD-X 4.00.19 +
+ Production Version +
+ Code Modification Date: 04.05.2009 +
+ Execution Time Stamp: 06.01.10 11.50.55 +
+++++
X: ==>
quit;
quit;

Number of warnings: 0

+++++
+ MAD-X 4.00.19 Finished normally +
+++++
cosmos:~ sterbini$
```

A GENERAL PURPOSE BEAM OPTICS CODE



For circular machines, beam lines and linacs...

- ▶ **Describe/document** optics parameters from machine description.
- ▶ **Design** a lattice for getting the desired properties (**matching**).
- ▶ **Simulate** beam dynamics, machine imperfections and machine operation.

A GENERAL PURPOSE BEAM OPTICS CODE

MAD-X is

- ▶ **multiplatforms** (Linux/OSX/WIN...),
- ▶ very **flexible** and possible to extend,
- ▶ made for complicated applications, **powerful** and rather complete,
- ▶ mainly designed **for large projects** (LEP, LHC, CLIC...).

MAD-X is **NOT**

- ▶ a program for teaching,
- ▶ (very) easy to use for beginners,
- ▶ coming with a graphical user interface.

IN LARGE PROJECTS (E.G., LHC):

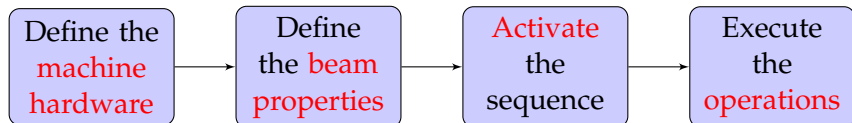


- ▶ Must be able to handle machines with $\geq 10^4$ elements,
- ▶ many simultaneous MAD-X users (LHC: more than 400 around the world): need consistent database,
- ▶ if you have many machines: ideally use only one design program.

DESCRIBE AN ACCELERATOR IN MAD-X

Goals...

- ▶ **Describe, optimize and simulate** a machine with several thousand elements eventually with magnetic elements shared by different beams, like in colliders.



MAD-X LANGUAGE

How does MAD-X get this info? Via text (**interpreter**).

- ▶ It accepts and executes statements, expressions...
- ▶ it can be used interactively (**input from command line**) or in batch (**input from file**),
- ▶ many features of a programming language (loops, if's, ...).

All input statements are analysed by a parser and checked.

- ▶ E.g. **assignments**: properties of machine elements, set up of the lattice, definition of beam properties, errors...
- ▶ E.g. **actions**: compute lattice functions, optimize and correct the machine...

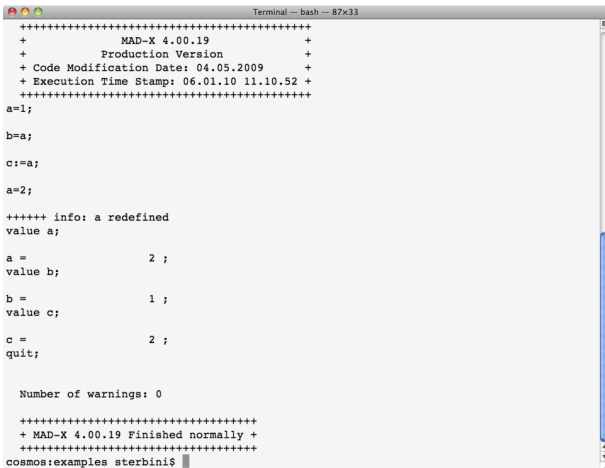
MAD-X INPUT LANGUAGE

- ▶ **Strong resemblance to "C" language** (but NO need for declarations and NOT case sensitive apart in expressions in inverted commas),
- ▶ free format, all statements are terminated with **;** (do not forget!),
- ▶ comment lines start with: **//** or **!** or is between **/*...*/**,
- ▶ Arithmetic expressions, including basic functions (**exp**, **log**, **sin**, **cosh**...), built-in random number generators and predefined constants (speed of the light, e , π , m_p , m_e ...).

In particular it is possible to use deferred assignments

- ▶ regular assignment: **a = b**, if **b** changes **a** does not,
- ▶ deferred assignment: **a := b**, if **b** changes **a** is updated too.

EXAMPLE: DEFERRED ASSIGNMENTS



```
Terminal -- bash -- 87x33
+++++
+          MAD-X 4.00.19          +
+      Production Version      +
+ Code Modification Date: 04.05.2009 +
+ Execution Time Stamp: 06.01.10 11.10.52 +
+++++
a=1;
b=a;
c:=a;
a=2;
+++++ info: a redefined
value a;

a =                2 ;
value b;

b =                1 ;
value c;

c =                2 ;
quit;

Number of warnings: 0

+++++
+ MAD-X 4.00.19 Finished normally +
+++++
cosmos:examples sterbini$
```

We use the **value** command to print the variables content.

DEFINITIONS OF THE LATTICE ELEMENTS

Generic pattern to define an element:

label: *keyword*, *properties*...;

- ▶ For a dipole magnet:
MBL: **SBEND**, **L=10.0**;
- ▶ For a quadrupole magnet:
MQ: **QUADRUPOLE**, **L=3.3**;
- ▶ For a sextupole magnet:
MSF: **SEXTUPOLE**, **L=1.0**;

In the previous examples we considered only the **L** property, that is the length in meters of the element.

THE STRENGTH OF THE ELEMENTS

The name of the parameter that define the **normalized magnetic strength** of the element depends on the element type.

- ▶ For dipole (horizontal bending) magnet is k_0 :

$$k_0 = \frac{1}{B\rho} B_y \text{ [in m}^{-1}\text{]}$$

- ▶ For quadrupole magnet is k_1 :

$$k_1 = \frac{1}{B\rho} \frac{\partial B_y}{\partial x} \text{ [in m}^{-2}\text{]}$$

- ▶ For sextupole magnet is k_2 :

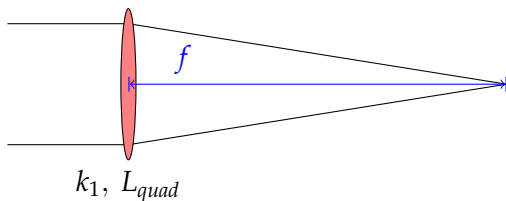
$$k_2 = \frac{1}{B\rho} \frac{\partial^2 B_y}{\partial x^2} \text{ [in m}^{-3}\text{]}$$

INTERLUDE

What does k_1 mean? It is related to the quad focal length².

$$\frac{1}{k_1 L_{quad}} = f \quad (1)$$

Assuming $k_1 = 10^{-1} \text{ m}^{-2}$ and $L_{quad} = 10^{-1} \text{ m}$ the $f = 10^2 \text{ m}$.



²thin lens approximation

EXAMPLE: DEFINITIONS OF ELEMENTS

- ▶ Sextupole magnet:

`ksf = 0.00156;`

MSF: `SEXTUPOLE, K2 = ksf, L=1.0;`

- ▶ Multipole magnet "thin" element:

MMQ: `MULTIPOLE, KNL = {k0 · l, k1 · l, k2 · l, k3 · l, ... };`

- ▶ LHC dipole magnet as **thick** element:

`length = 14.3;`

`p = 7000;`

`angleLHC = 8.33 * clight * length/p;`

MBL: `SBEND, ANGLE = angleLHC;`

THE LATTICE SEQUENCE

A lattice sequence is an ordered collection of machine elements. Each element has a position in the sequence that can be defined wrt the CENTRE, EXIT or ENTRY of the element and wrt the sequence start or the position of an other element:

```
label: SEQUENCE, REFER=CENTRE, L=length;
...;
...;
...here specify position of all elements...;
...;
...;
ENDSEQUENCE;
```

EXAMPLE OF SEQUENCE: LHC (TOO TOUGH?)

```

Terminal - vim - 114x36
640 MSS : SEXTUPOLE, L := 1.MSS, Kmax := Kmax_MSS, Kmin := Kmin_MSS, Calib := Kmax_MSS / Imax_MSS;
641 //----- SOLENOID -----
642 MBAS2 : SOLENOID, L := 1.MBAS2;
643 MBCS2 : SOLENOID, L := 1.MBCS2;
644 MBLS2 : SOLENOID, L := 1.MBLS2;
645 //----- VCORRECTOR -----
646 MCBVCV : VCORRECTOR, L := 1.MCBVCV, Kmax := Kmax_MCBVCV, Kmin := Kmin_MCBVCV, Calib := Kmax_MCBVCV / Imax_MCBVCV;
647 MCBV : VCORRECTOR, L := 1.MCBV, Kmax := Kmax_MCBV, Kmin := Kmin_MCBV, Calib := Kmax_MCBV / Imax_MCBV;
648 MCBWV : VCORRECTOR, L := 1.MCBWV, Kmax := Kmax_MCBWV, Kmin := Kmin_MCBWV, Calib := Kmax_MCBWV / Imax_MCBWV;
649 MCBXV : VCORRECTOR, L := 1.MCBXV, Kmax := Kmax_MCBXV, Kmin := Kmin_MCBXV, Calib := Kmax_MCBXV / Imax_MCBXV;
650 MCBYV : VCORRECTOR, L := 1.MCBYV, Kmax := Kmax_MCBYV, Kmin := Kmin_MCBYV, Calib := Kmax_MCBYV / Imax_MCBYV;
651 //----- VKICKER -----
652 MBAW : VKICKER, L := 1.MBAW, Kmax := Kmax_MBAW, Kmin := Kmin_MBAW, Calib := Kmax_MBAW / Imax_MBAW;
653 MBWMD : VKICKER, L := 1.MBWMD, Kmax := Kmax_MBWMD, Kmin := Kmin_MBWMD, Calib := Kmax_MBWMD / Imax_MBWMD;
654 MBXWT : VKICKER, L := 1.MBXWT, Kmax := Kmax_MBXWT, Kmin := Kmin_MBXWT, Calib := Kmax_MBXWT / Imax_MBXWT;
655
656 //----- LHC SEQUENCE -----
657 LHCb1 : SEQUENCE, refer = CENTRE, L = LHLENGTH;
658 IP1:OMK,
659   at = pIP1+IP1OFS.B1*DS, mech_sep = 0, slot_id = 2209454,
660   MBAS2.1R1:MBAS2,
661   at = 20.015+(0-IP1OFS.B1)*DS, mech_sep = 0, slot_id = 102103,
662   TAS.1R1:TAS,
663   at = 21.475+(0-IP1OFS.B1)*DS, mech_sep = 0, slot_id = 104594,
664   BPMSW.1R1:BPMSW,
665   at = 26.15+(0-IP1OFS.B1)*DS, mech_sep = 0, slot_id = 282126, assembly_id = 102104,
666   MQXA.1R1:MQXA,
667   at = 29.842+(0-IP1OFS.B1)*DS, mech_sep = 0, slot_id = 282213, assembly_id = 102104,
668   MCBXH.1R1:MCBXH,
669   at = 29.842+(0-IP1OFS.B1)*DS, mech_sep = 0, slot_id = 282212, assembly_id = 102104,
670   MCBXV.1R1:MCBXV,
671   at = 31.529+(0-IP1OFS.B1)*DS, mech_sep = 0, slot_id = 241889, assembly_id = 102105,
672   BPMS.2R1.B1:BPMS,
673   at = 34.8+(0-IP1OFS.B1)*DS, mech_sep = 0, slot_id = 241890, assembly_id = 102105,
674   MQXB.A2R1:MQXB,
675   at = 38.019+(0-IP1OFS.B1)*DS, mech_sep = 0, slot_id = 249450, assembly_id = 102105,
676   MCBXH.2R1:MCBXH,
677   at = 38.019+(0-IP1OFS.B1)*DS, mech_sep = 0, slot_id = 249451, assembly_id = 102105,
678   MCBXV.2R1:MCBXV,
679   at = 41.3+(0-IP1OFS.B1)*DS, mech_sep = 0, slot_id = 241892, assembly_id = 102105,
680   MQXB.B2R1:MQXB,
681   at = 45.342+(0-IP1OFS.B1)*DS, mech_sep = 0, slot_id = 241893, assembly_id = 102106,
682   TASB.3R1:TASB,
683   at = 46.608+(0-IP1OFS.B1)*DS, mech_sep = 0, slot_id = 282127, assembly_id = 102106,
684   MQSX.3R1:MQSX,
685   at = 50.15+(0-IP1OFS.B1)*DS, mech_sep = 0, slot_id = 241895, assembly_id = 102106,
686   MQXA.3R1:MQXA,
687   at = 53.814+(0-IP1OFS.B1)*DS, mech_sep = 0, slot_id = 249456, assembly_id = 102106,
688   MCBXH.3R1:MCBXH,
689   at = 53.814+(0-IP1OFS.B1)*DS, mech_sep = 0, slot_id = 249457, assembly_id = 102106,
690   MCBXV.3R1:MCBXV,

```

BEAM DEFINITION & SEQUENCE ACTIVATION

Generic pattern to define the beam:

label: **BEAM**, **PARTICLE**=x, **ENERGY**³=y,...;

e.g., **BEAM**, **PARTICLE**=proton, **ENERGY**=7000; // in GeV

After a sequence has been read, it can be activated:

USE, **SEQUENCE**=sequence_label;

e.g., **USE**, **SEQUENCE**=lhc1;

The **USE** command expands the specified sequence, inserts the drift spaces and makes it active.

³It is the TOTAL energy!

DEFINITION OF OPERATIONS

Once the sequence is activated we can perform operations on it.

- ▶ Calculation of Twiss parameters around the machine (**very important**) in order to know, for stable sequences, their main optical parameters.

TWISS, **SEQUENCE**=sequence_label; // periodic solution

TWISS, **SEQUENCE**=sequence_label, betx=1; // IC solution

- ▶ Production of graphical output of the main optical function (e.g., β -functions):

PLOT, **HAXIS**=s, **VAXIS**=betx,bety;

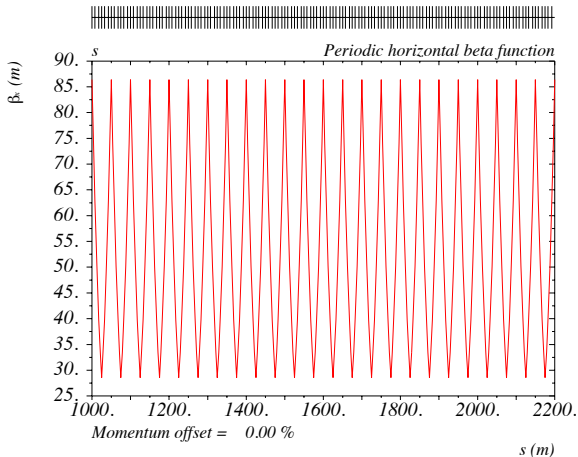
Example

TWISS, **SEQUENCE**=juaseq, **FILE**=twiss.out;

PLOT, **HAXIS**=s, **VAXIS**=betx, bety, **COLOUR**=100;

EXAMPLE OF THE TWISS FILE

```
* NAME          S          BETX          BETY
$ %s           %le          %le          %le
"QF"           1.5425        107.5443191  19.4745051
"QD"           33.5425       19.5134888   107.4973054
"QF"           65.5425       107.5443191  19.4745051
"QD"           97.5425       19.5134888   107.4973054
"QF"           129.5425      107.5443191  19.4745051
"QD"           161.5425      19.5134888   107.4973054
"QF"           193.5425      107.5443191  19.4745051
"QD"           225.5425      19.5134888   107.4973054
"QF"           257.5425      107.5443191  19.4745051
"QD"           289.5425      19.5134888   107.4973054
"QF"           321.5425      107.5443191  19.4745051
"QD"           353.5425      19.5134888   107.4973054
"QF"           385.5425      107.5443191  19.4745051
"QD"           417.5425      19.5134888   107.4973054
"QF"           449.5425      107.5443191  19.4745051
"QD"           481.5425      19.5134888   107.4973054
"QF"           513.5425      107.5443191  19.4745051
"QD"           545.5425      19.5134888   107.4973054
"QF"           577.5425      107.5443191  19.4745051
"QD"           609.5425      19.5134888   107.4973054
....
....
```

EXAMPLE OF THE GRAPHICAL OUTPUT (**PS FORMAT**)

MATCHING GLOBAL PARAMETERS

It is possible to modify the optical parameters of the machine using the MATCHING module of MAD-X.

- ▶ Adjust magnetic strengths to get desired properties (e.g., tune Q, chromaticity dQ),
- ▶ Define the **properties** to match and the **parameters** to vary.

Example:

```

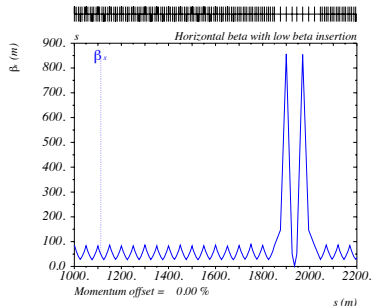
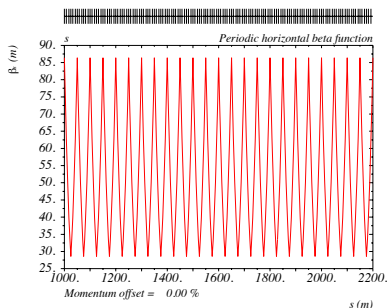
MATCH, SEQUENCE=sequence_name;
  GLOBAL, Q1=26.58; // H-tune
  GLOBAL, Q2=26.62; // V-tune
  VARY, NAME= kqf, STEP=0.00001;
  VARY, NAME = kqd, STEP=0.00001;
  LMDIF, CALLS=50, TOLERANCE=1e-6; // method adopted
ENDMATCH;

```

OTHER TYPES OF MATCHING I

Local matching and performance matching:

- ▶ Local optical functions (insertions, local optics change),
- ▶ any user defined variable.



OTHER TYPES OF MATCHING II

Local matching and performance matching:

- ▶ Local optical functions (insertions, local optics change),
- ▶ any user defined variable.

Example:

```
MATCH, SEQUENCE=sequence_name;  
  CONSTRAINT, range=#e, BETX=50;  
  CONSTRAINT, range=#e, ALFX=-2;  
  VARY, NAME= kqf, STEP=0.00001;  
  VARY, NAME = kqd, STEP=0.00001;  
  JACOBIAN, CALLS=50, TOLERANCE=1e-6;  
ENDMATCH;
```

GENERAL CONSIDERATIONS ON MAD-X SYNTAX

Input language seems heavy, but:

- ▶ can be interfaced to data base and to other programs (e.g., Python, MatlabTM...),
- ▶ programs exist to generate the input interactively,
- ▶ allows web based applications,
- ▶ allows interface to operating system.

MAD-X can estimate the machine performance by:

- ▶ studying of long term stability with multipolar component,
- ▶ taking into account the tolerances for machine elements,
- ▶ simulating operation of the machine (imperfections,...).

DO WE USE MAD-X FOR EVERYTHING? **NO!**

MAD-X is an **optics** program (**single particle dynamics**).

MAD-X has limitations where

- ▶ **multi particle and multi bunch** simulations are required,
- ▶ **machine is not static**, i.e., beam changes its own environment (space charge, instabilities, beam-beam effects...),
- ▶ requires self-consistent treatment, **computation of fields and forces**,
- ▶ execution **speed** is an issue,
- ▶ for detailed studies dedicated programs are needed, **but often with I/O interface to MAD-X**.

"HELLO WORLD!" INPUT FILE

```
Terminal - vim - 105x36
1 /****Definition of elements****/
2 qfType:QUADRUPOLE, L=1.5, K1:=kf;
3 qdType:QUADRUPOLE, L=1.5, K1:=kd;
4
5 /****Definition of the sequence****/
6 fodo:SEQUENCE, REFER=exit, L=10;
7 qf: qfType, at=5;
8 qd: qdType, at=10;
9 ENDSEQUENCE;
10
11 /****Definition of the strength****/
12 kf=+0.2985;
13 kd=-0.2985;
14
15 /****Definition of the beam****/
16 beam, particle=proton, energy=7001;
17
18 /****Activation of the sequence****/
19 use, sequence=fodo;
20
21 /****Operations****/
22 twiss;
23 plot, HAXIS=s, VAXIS=betx, bety;
24
25 /****Matching****/
26 MATCH, sequence=fodo;
27   GLOBAL, Q1=.25;
28   GLOBAL, Q2=.25;
29   VARY, NAME=kf, STEP=0.00001;
30   VARY, NAME=kd, STEP=0.00001;
31   LMDIF, CALLS=50, TOLERANCE=1e-8;
32 ENDMATCH;
33
34 /****Best Regards****/
35 QUIT
"fodo.mad" 35L, 689C
```

"HELLO WORLD!" OUTPUT (1)

```
Terminal -- bash -- 105x36
cosmos:examples sterbini$ madx<fodo.mad

+++++
+          MAD-X 4.00.19          +
+      Production Version      +
+ Code Modification Date: 04.05.2009  +
+ Execution Time Stamp: 07.01.10 12.04.00 +
+++++
/****Definition of elements****/

qfType:QUADRUPOLE, L=1.5, K1=kf;

qdType:QUADRUPOLE, L=1.5, K1=kd;

/****Definition of the sequence****/

fodo:SEQUENCE, REFER=exit, L=10;

qf: qfType, at=5;

qd: qdType, at=10;

ENDSEQUENCE;

/****Definition of the strength****/

kf=+0.2985;

kd=-0.2985;
```

"HELLO WORLD!" OUTPUT (2)

```

Terminal — bash — 105x36
/****Definition of the beam****/
beam, particle=proton, energy=7001;

/****Activation of the sequence****/
use, sequence=fodo;

/****Operations****/
twiss;

enter Twiss module
+++++ info: Zero value of SIGT replaced by 1.
+++++ info: Zero value of SIGE replaced by 1/1000.

iteration: 1 error: 0.000000E+00 deltap: 0.000000E+00
orbit: 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00

+++++ table: summ

      length          orbit5          alfa          gammatr
      10              -0          -3.30872245e-24  -5.497558139e+11

      q1              dq1              betxmax          dxmax
0.4877944671        -8.265035446          208.1244543          0

      dxrms          xcomax          xcorms          q2
      0              0              0              0.4877944671

      dq2              betymax          dymax          dyrms
-8.265035446        208.1244543          0              0

```

"HELLO WORLD!" OUTPUT (3)

```

Terminal — bash — 105x36
twiss;

enter Twiss module
+++++ info: Zero value of SIGT replaced by 1.
+++++ info: Zero value of SIGE replaced by 1/1000.

iteration: 1 error: 0.000000E+00 deltap: 0.000000E+00
orbit: 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00 0.000000E+00

+++++ table: summ

      length      orbit5      alfa      gammatr
      10          -0      -3.30872245e-24      -5.497558139e+11

      q1          dq1          betxmax          dxmax
0.4877944671      -8.265035446      208.1244543          0

      dxrms          xcomax          xcorms          q2
0          0          0          0.4877944671

      dq2          betymax          dymax          dyrms
-8.265035446      208.1244543          0          0

      ycomax          ycorms          deltap          synch_1
0          0          0          0

      synch_2          synch_3          synch_4          synch_5
0          0          0          0

plot, HAXIS=s, VAXIS=betx, bety;

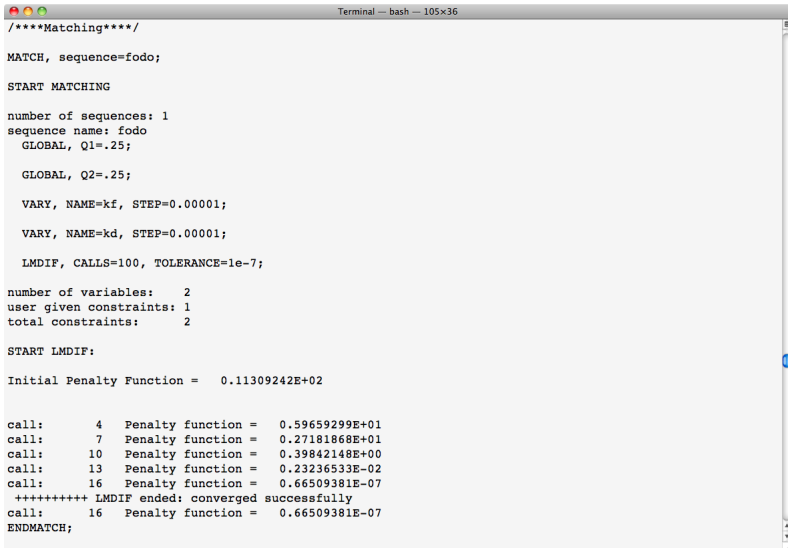
+++++ info: Zero value of SIGT replaced by 1.
+++++ info: Zero value of SIGE replaced by 1/1000.

GX PLOT-X11 1.50 initialized

plot number = 1

```

"HELLO WORLD!" OUTPUT (4)



```
Terminal — bash — 105x36
/****Matching****/

MATCH, sequence=fodo;

START MATCHING

number of sequences: 1
sequence name: fodo
  GLOBAL, Q1=.25;

  GLOBAL, Q2=.25;

  VARY, NAME=kf, STEP=0.00001;

  VARY, NAME=kd, STEP=0.00001;

  LMDIF, CALLS=100, TOLERANCE=1e-7;

number of variables:    2
user given constraints: 1
total constraints:     2

START LMDIF:

Initial Penalty Function = 0.11309242E+02

call:      4  Penalty function = 0.59659299E+01
call:      7  Penalty function = 0.27181868E+01
call:     10  Penalty function = 0.39842148E+00
call:     13  Penalty function = 0.23236533E-02
call:     16  Penalty function = 0.66509381E-07
+++++++ LMDIF ended: converged successfully
call:     16  Penalty function = 0.66509381E-07
ENDMATCH;
```


"HELLO WORLD!" OUTPUT (5)

```

Terminal — bash — 105x36

MATCH SUMMARY

Node_Name          Constraint  Type  Target Value      Final Value      Penalty
-----
Global constraint:  q1         4     2.50000000E-01    2.50018141E-01    3.29107276E-08
Global constraint:  q2         4     2.50000000E-01    2.50018330E-01    3.35986532E-08

Final Penalty Function = 6.65093808e-08

Variable           Final Value  Initial Value  Lower Limit  Upper Limit
-----
kf                 2.11034e-01  2.98500e-01  -1.00000e+20  1.00000e+20
kd                 -2.11034e-01 -2.98500e-01 -1.00000e+20  1.00000e+20

END MATCH SUMMARY

VARIABLE "TAR" SET TO 6.65093808e-08

/****Best Regards****/

QUIT;

Number of warnings: 0

+++++
+ MAD-X 4.00.19 Finished normally +
+++++

```