# Introduction to MAD-X

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Introduction

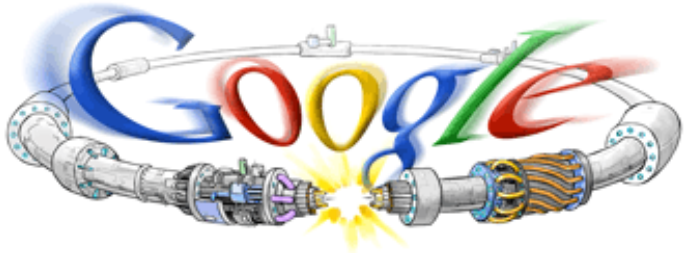
MAD-X syntax

Daily life

"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!

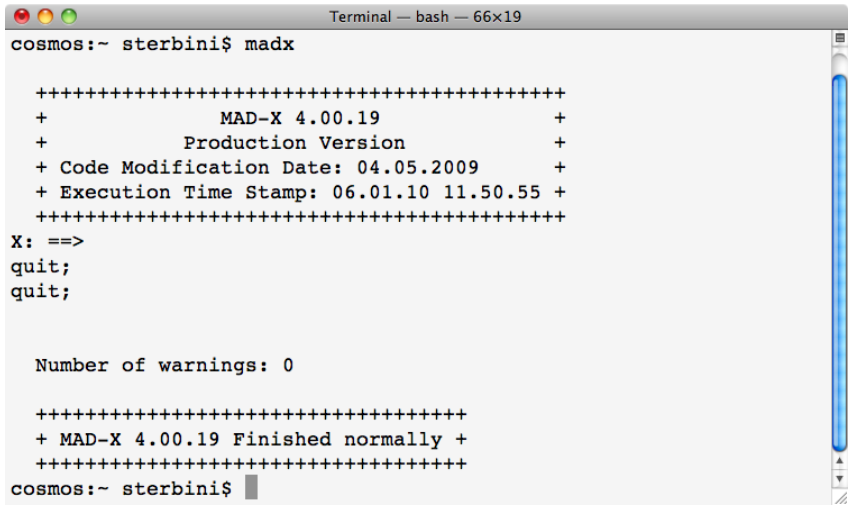
A lot of material on the web…



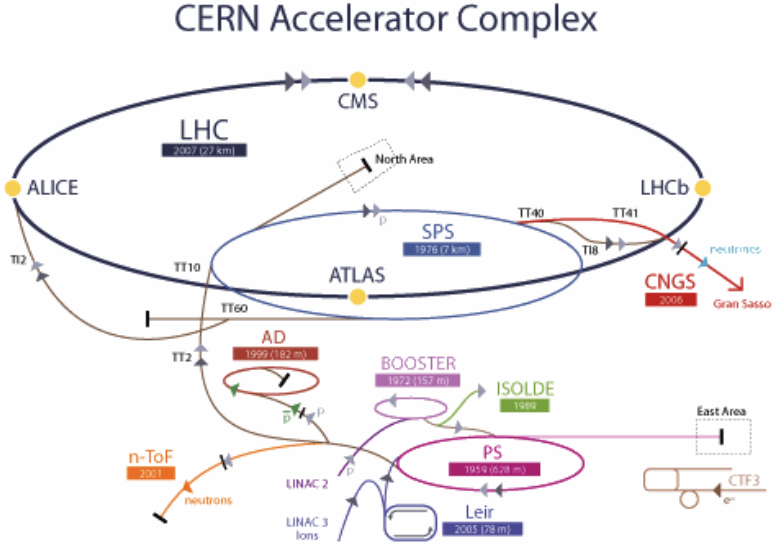

- By googling "madx", you get the MAD-X homepage.
- To wet your appetite, you can google "MAD-X primer".
- To go in details, you can google "MAD-X manual".

# 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 20 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).



# 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 easy 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.

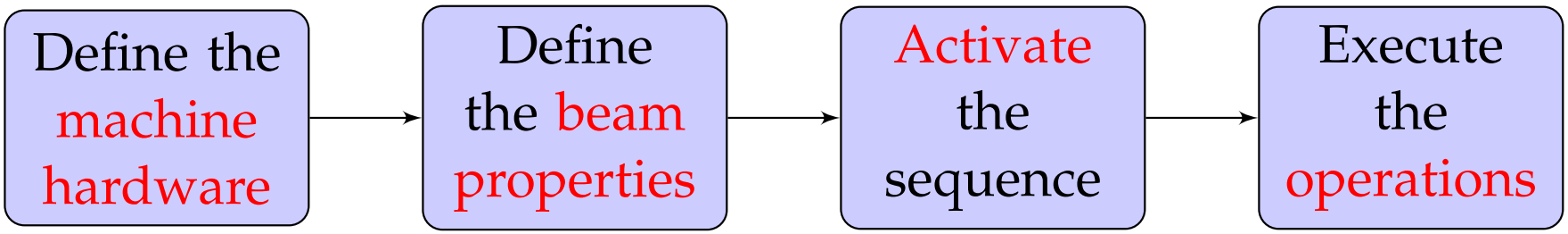
# In large projects (e.g., LHC):

- 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. . .

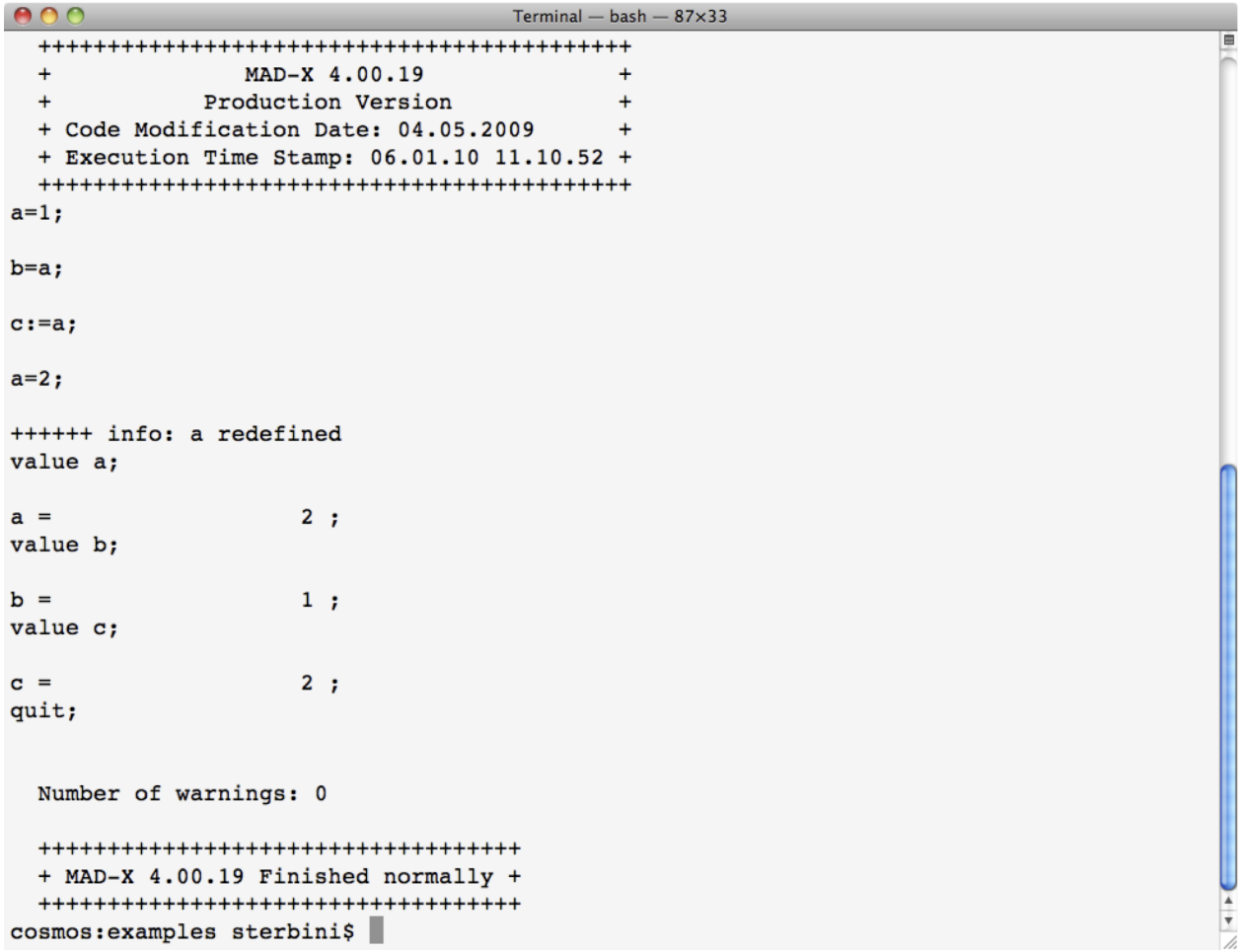
# MAD-X INPUT LANGUAGE

- 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, $e$, $\pi$, $m_p$, $m_e$...).

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




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 $k_0$:

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

- For quadrupole magnet is $k_1$:

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

- For sextupole magnet is $k_2$:

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

# EXAMPLE: DEFINITIONS OF ELEMENTS

- Sextupole magnet:

  ksf = 0.00156;

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

- Multipole magnet "thin" element:

  MMQ: MULTIPOLE, KNL = $\{k0 \cdot l, k1 \cdot l, k2 \cdot l, k3 \cdot l, \ldots\}$;

- 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 — 114×36

```
640 MSS : SEXTUPOLE, L := l.MSS, Kmax := Kmax_MSS, Kmin := Kmin_MSS, Calib := Kmax_MSS / Imax_MSS;
641 //---------------------- SOLENOID       -------------------------------------------
642 MBAS2 : SOLENOID, L := l.MBAS2;
643 MBCS2 : SOLENOID, L := l.MBCS2;
644 MBLS2 : SOLENOID, L := l.MBLS2;
645 //---------------------- VCORRECTOR     -------------------------------------------
646 MCBCV : VCORRECTOR, L := l.MCBCV, Kmax := Kmax_MCBCV, Kmin := Kmin_MCBCV, Calib := Kmax_MCBCV / Imax_MCBCV;
647 MCBV : VCORRECTOR, L := l.MCBV, Kmax := Kmax_MCBV, Kmin := Kmin_MCBV, Calib := Kmax_MCBV / Imax_MCBV;
648 MCBWV : VCORRECTOR, L := l.MCBWV, Kmax := Kmax_MCBWV, Kmin := Kmin_MCBWV, Calib := Kmax_MCBWV / Imax_MCBWV;
649 MCBXV : VCORRECTOR, L := l.MCBXV, Kmax := Kmax_MCBXV, Kmin := Kmin_MCBXV, Calib := Kmax_MCBXV / Imax_MCBXV;
650 MCBYV : VCORRECTOR, L := l.MCBYV, Kmax := Kmax_MCBYV, Kmin := Kmin_MCBYV, Calib := Kmax_MCBYV / Imax_MCBYV;
651 //---------------------- VKICKER        -------------------------------------------
652 MBAW : VKICKER, L := l.MBAW, Kmax := Kmax_MBAW, Kmin := Kmin_MBAW, Calib := Kmax_MBAW / Imax_MBAW;
653 MBWMD : VKICKER, L := l.MBWMD, Kmax := Kmax_MBWMD, Kmin := Kmin_MBWMD, Calib := Kmax_MBWMD / Imax_MBWMD;
654 MBXWT : VKICKER, L := l.MBXWT, Kmax := Kmax_MBXWT, Kmin := Kmin_MBXWT, Calib := Kmax_MBXWT / Imax_MBXWT;
655
656 //------------------------ LHC SEQUENCE                  -------------------------
657 LHCB1 : SEQUENCE, refer = CENTRE, L = LHCLENGTH;
658 IP1:OMK,                  at= pIP1+IP1OFS.B1*DS;
659   MBAS2.1R1:MBAS2,        at= 1.5+(0-IP1OFS.B1)*DS, mech_sep= 0, slot_id= 2209454,
660   TAS.1R1:TAS,            at= 20.015+(0-IP1OFS.B1)*DS, mech_sep= 0, slot_id= 102103,
661   BPMSW.1R1.B1:BPMSW,     at= 21.475+(0-IP1OFS.B1)*DS, mech_sep= 0, slot_id= 104594,
662   MQXA.1R1:MQXA,          at= 26.15+(0-IP1OFS.B1)*DS, mech_sep= 0, slot_id= 282126, assembly_id= 102104,
663   MCBXH.1R1:MCBXH,        at= 29.842+(0-IP1OFS.B1)*DS, mech_sep= 0, slot_id= 282213, assembly_id= 102104,
664   MCBXV.1R1:MCBXV,        at= 29.842+(0-IP1OFS.B1)*DS, mech_sep= 0, slot_id= 282212, assembly_id= 102104,
665   BPMS.2R1.B1:BPMS,       at= 31.529+(0-IP1OFS.B1)*DS, mech_sep= 0, slot_id= 241889, assembly_id= 102105,
666   MQXB.A2R1:MQXB,         at= 34.8+(0-IP1OFS.B1)*DS, mech_sep= 0, slot_id= 241890, assembly_id= 102105,
667   MCBXH.2R1:MCBXH,        at= 38.019+(0-IP1OFS.B1)*DS, mech_sep= 0, slot_id= 249450, assembly_id= 102105,
668   MCBXV.2R1:MCBXV,        at= 38.019+(0-IP1OFS.B1)*DS, mech_sep= 0, slot_id= 249451, assembly_id= 102105,
669   MQXB.B2R1:MQXB,         at= 41.3+(0-IP1OFS.B1)*DS, mech_sep= 0, slot_id= 241892, assembly_id= 102105,
670   TASB.3R1:TASB,          at= 45.342+(0-IP1OFS.B1)*DS, mech_sep= 0, slot_id= 241893, assembly_id= 102106,
671   MQSX.3R1:MQSX,          at= 46.608+(0-IP1OFS.B1)*DS, mech_sep= 0, slot_id= 282127, assembly_id= 102106,
672   MQXA.3R1:MQXA,          at= 50.15+(0-IP1OFS.B1)*DS, mech_sep= 0, slot_id= 241895, assembly_id= 102106,
673   MCBXH.3R1:MCBXH,        at= 53.814+(0-IP1OFS.B1)*DS, mech_sep= 0, slot_id= 249456, assembly_id= 102106,
674   MCBXV.3R1:MCBXV,        at= 53.814+(0-IP1OFS.B1)*DS, mech_sep= 0, slot_id= 249457, assembly_id= 102106,
```

# BEAM DEFINITION & SEQUENCE ACTIVATION

Generic pattern to define the beam:

label: BEAM, PARTICLE=x, ENERGY=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.

# 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;

- Production of graphical output of the main optical function (e.g., $\beta$-functions):
  PLOT, HAXIS=s, VAXIS=betx,bety;

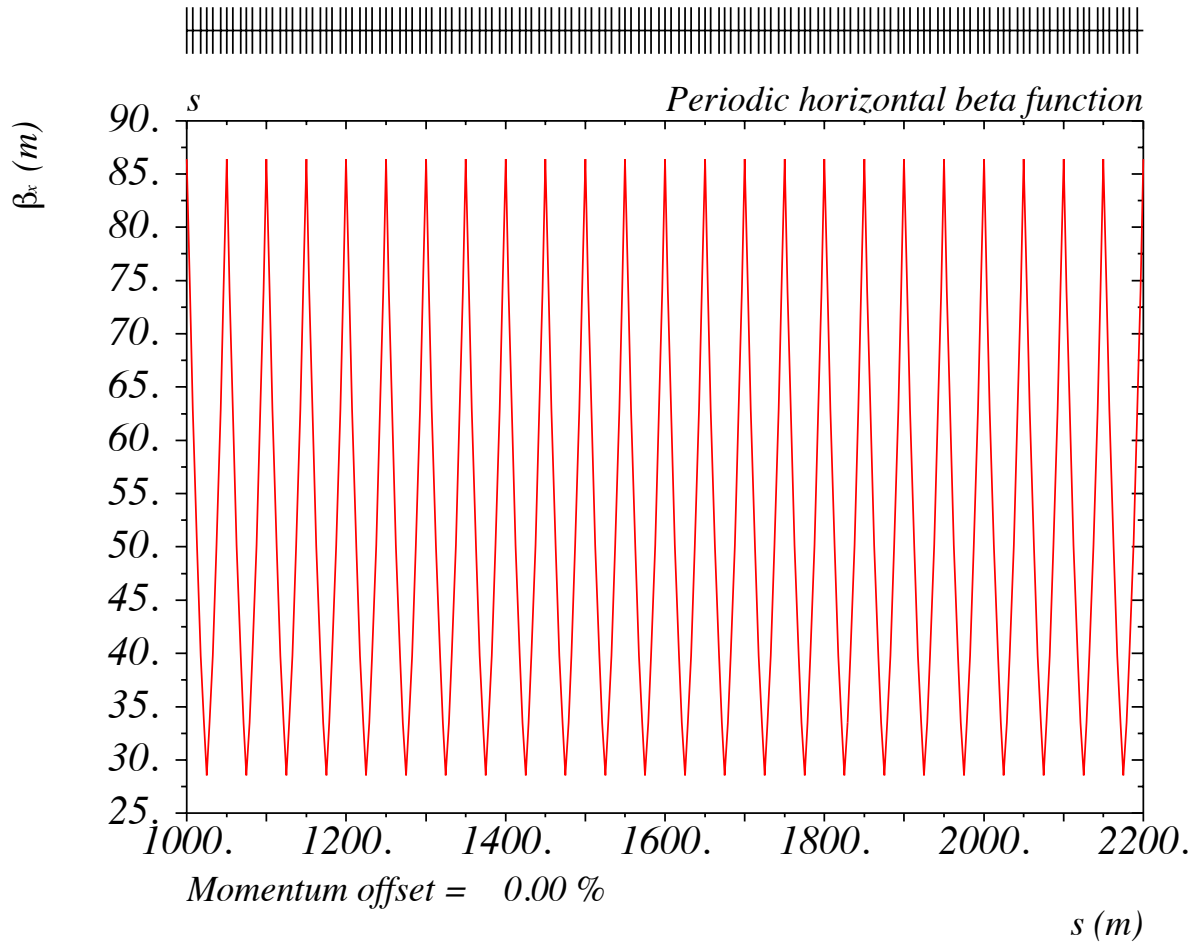
Example

```
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.

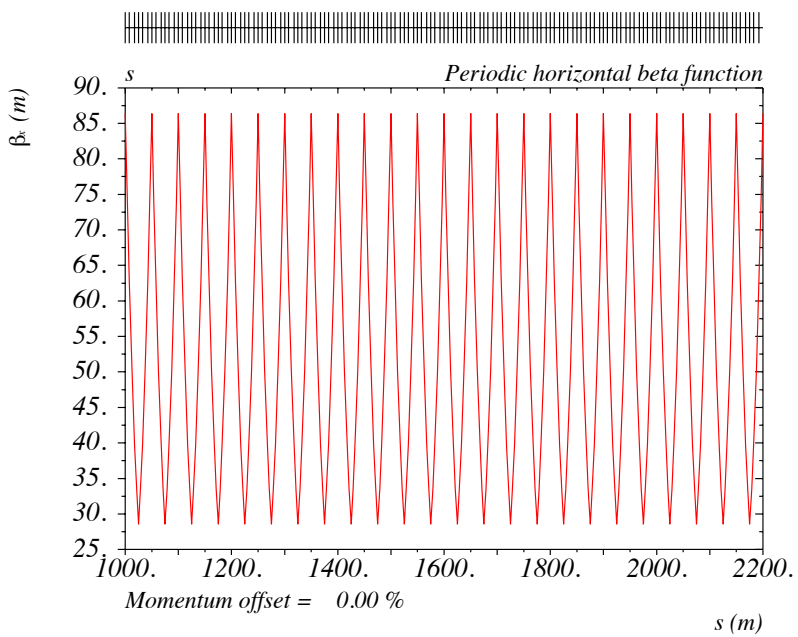
Example:

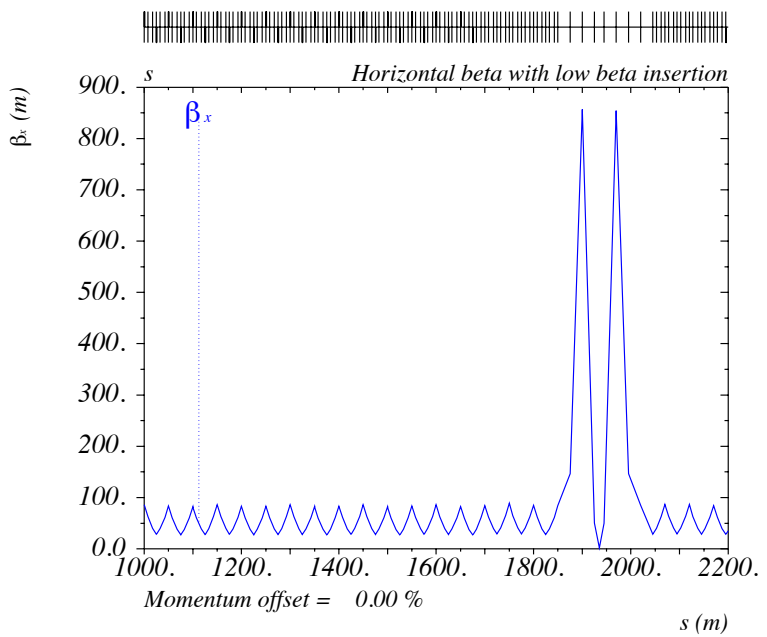
```
MATCH, SEQUENCE=sequence_name;
   GLOBAL, Q1=26.58;//H-tune
   GLOBAL, Q2=26.62;//V-tune
   VARY, NAME= kqf, STEP=0.00001;
   VARY, NAME = kqd, STEP=0.00001;
   LMDIF, CALLS=50, TOLERANCE=1e-6;//method adopted
ENDMATCH;
```

# Other types of matching

Local matching and performance matching:

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



# General considerations on MAD-X syntax

Input language seems heavy, but:

- can be interfaced to data base and to other programs (e.g., Mathematica™, Matlab™...),
- 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.

# SOME USEFUL TIPS FOR THE TUTORIALS (WIN)

## Additional software needed...

- Most of the input/output of MADX is in ASCII files: you can read/write/edit them using Notepad++. The graphical output of MAD is on PS format: you can use Evince to open it.

## Tricks for beginners:

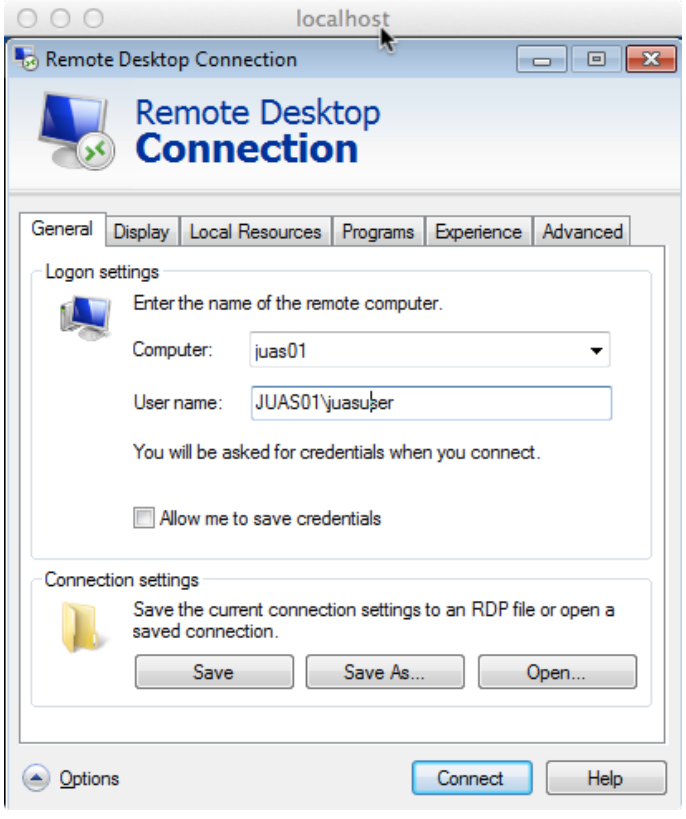
- a working MAD-X environment has been set up for you
- to make all happy, we will use a unix-lixe shell (Cygwin) in a WIN OS.
- once you have the input (e.g., whatever.inp), execute it by:
  - 1. "CALL, FILE=whatever.inp;" at the MADX prompt,
  - 2. madx<whatever.inp" at the shell (preferred).

# REMOTE CERN MACHINES (SOMEONE MISSING?)

| Family name | Name | Remote machine |
|---|---|---|
| ABREU FERNANDES | Miguel Filipe | JUAS01 |
| AZIZI | Roxana | JUAS02 |
| BANFI | Danilo | JUAS03 |
| BARTOZIK | Marcin | JUAS04 |
| BATTAGLIA | Giorgio | JUAS05 |
| BEN ZID | Oussema | JUAS06 |
| BRACCALENTI | Edoardo | JUAS07 |
| CIAMBRELLA | Massimo | JUAS08 |
| CRUZ ALANIZ | Emilia | JUAS09 |
| DAYYANI KELISANI | Mohsen | JUAS10 |
| EL MHARI | Charaf | JUAS11 |
| ESTEBAN MARTI | Sergi | JUAS12 |
| FRASCIELLO | Oscar | JUAS13 |
| GINER NAVARRO | Jorge | JUAS14 |
| HAJ TAHAR | Malek | JUAS15 |
| HOFMANN | Thomas | JUAS16 |
| HUSCHAUER | Alexander | JUAS17 |
| KALAMAIKO | Anatolii | JUAS18 |
| KRAMMER | Jakob | JUAS19 |
| KRAUS | Ingrid | JUAS20 |
| KURICHIYANIL | Neeraj | JUAS21 |
| LA FERLA | Marco | JUAS22 |
| LABUSSIERE | Etienne | JUAS23 |
| LAGIER | Stphane | JUAS24 |
| LEDERER | Stephan | JUAS25 |
| LEO | Stefano | JUAS26 |
| LIEBERWIRTH | Alice | JUAS27 |
| MEREGHETTI | Alessio | JUAS28 |
| NAVARRO QUIRANTE | Jose Luis | JUAS29 |
| NAVEED | Sehar | JUAS30 |
| NUEL GAVALDA | Xavier | JUAS31 |
| PAPADOPOULOU | Stefania | JUAS32 |
| PATECKI | Marcin | JUAS33 |
| PATEL | Vivek | JUAS34 |
| RAJABI | Ali | JUAS35 |
| RAUCY | Christopher | JUAS36 |
| REY | Solenne | JUAS37 |
| SANAYE HAJARI | Shahin | JUAS38 |
| SOFRANAC | Martina | JUAS39 |
| STEINMANN | Johannes | JUAS40 |
| TAKABATAKE | Mao | JUAS41 |
| UNGETHM | Carina | JUAS42 |
| ZHENG | Dawei | JUAS43 |
| ZWICKER | Benjamin | JUAS44 |

# ACCESS REMOTE MACHINE JUASXX

- Computer: JUASXX
- User: JUASXX\ juasuser
- PWD: Juas12User
- Cygwin (UNIX shell in WIN). From the shell with the command "open" you open the Win Explorer (edit inp, read out)
- Use your assigned PC!



# "Hello World!" input file

Terminal — vim — 105×36

```
 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 — 105×36

```
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 — 105×36

```
/****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 — 105×36

```
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.

 GXPLOT-X11  1.50 initialized

 plot number =            1
```

# "HELLO WORLD!" OUTPUT (4)

Terminal — bash — 105×36

```
/****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 — 105×36

```
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 +
  ++++++++++++++++++++++++++++++++++
```