CI-Beam-105

Lattice Design and Computational Dynamics III

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Scope of MADX in this lecture

- Description of the basic concepts and the language
- How to compute optical functions
- Perform “matching”:
  - Beam dimensions
  - Tune, chromaticity
- Machine with imperfections and their correction
- Design of insertions
  - e.g. Dispersion suppressor
- Advanced optimisation or particle tracking code (PTC)

Why MADX?

- A long line of development
- Used at CERN since more than 20 years for machine design and simulation (PS, SPS, LEP, LHC, CLIC, beam lines…)
- Existing versions MAD8, MAD9, MADX (with PTC)
- Increasing and organised support and website in recent years: http://mad.web.cern.ch/mad/
- Running on all systems
- Source is free and easy to extend
- Input easy to understand

Typical Input

- Description of the machine
  - ➡Definition of each machine element
  - ➡Attributes of elements
  - ➡Position of elements
- Description of the beam(s)
- Commands regarding the desired process.

How does it work?

- MADX is an interpreter
  - accepts and executes statements
  - statement can be assignments or expressions
  - can be used interactively or in batch mode
- MADX has many features of a programming language (loops, if conditions, macros, subroutines ...)

MADX Input Language

- Strong resemblance to C/C++
- All statements must be terminated with **;**
- Lines can be commented out with **** or **!**
- Arithmetic expressions, including basic functions (**exp, log, sin, cosh, ...**)
- Built-in random number generators for various distributions
- Deferred expressions (**:=**)
- Predefined constants (**clight, e, pi, mp, me, ...**)

MADX Conventions

- Not case sensitive
- Elements are placed along the reference orbit (variable **s**).
- Horizontal (assumed bending plane) and vertical variables are **x** and **y**
- Describes a local coordinate system moving along s
    - x=y=0 follows the curvilinear system
- MADX variables are floating point numbers (double precision)
- Variables can be used in expressions
    - ANGLE = 2*PI/NBEND
- The assignment symbols = and := (deferred assignment) have very different behaviour
    - DX = GAUSS()*1.5E-3;

      The value is calculated **once** and kept in DX
    - DX := GAUSS()*1.5E-3;

      The value is calculated **every time** DX is used.

Let’s Try

```
x: ==> angle = 2*pi/1232;
x: ==> value, angle;
x: ==> value, sin(1,0)*2;
x: ==> dx = gauss()*2.0;
x: ==> value, dx;
x: ==> value, dx;
x: ==> dx := gauss()*2.0;
x: ==> value, dx;
x: ==> value, dx;
```

Let's Try

Batch mode:

```
> madx

X: ==> call, file=my_file.madx;
```

```
> ./madx < my_file.madx    (unix)

>.\madx < my_file.madx     (Windows)
```

MADX Input Statements

- Typical assignments
  - Properties of machine elements
  - Setting up a lattice
  - Definition of beam properties (particle type, energy, emittance etc.)
  - Assignment of errors and imperfections
- Typical actions
  - Compute lattice functions
  - Correct machine errors
  - Matching of subsections

Definition of machine elements

- All machine elements have to be described
- They can be described individually or
- as a family **("class")** of elements (i.e. all elements with the same properties)
- All elements can have unique names (not necessarily)
- MADX "keywords" are used to define the type of an element
- General format:

name:keyword, attributes

Example: Definition of machine elements

- Dipole (bending) magnet

```
MBL: SBEND, L=10.0, ANGLE = 0.0145444;
```

- Quadrupole (focusing) magnet

```
MQ: QUADRUPOLE, L=3.3, K1 = 1.23E-02;
```

- Sextupole magnet

```
ksf = 0.00156;
MSF: SEXTUPOLE, K2 := ksf, L=1.0;
```

Example: Definition of strength of the elements

- **Dipole (bending) magnet**

$$k_0 = \frac{1}{p/c} B_y[T] \quad \left(= \tfrac{1}{\rho} = \tfrac{angle}{\ell}[rad/m]\right)$$

```
DIP01: SBEND, L=10.0, ANGLE = angle, K0=k0;
DIP02: MBL;     ! belongs to MBL family
DIP03: MBL;     ! an instance of MBL class
```

- **Quadrupole (focusing) magnet**

$$k_1 = \frac{1}{p/c} \frac{\partial B_y}{\partial x} [T/m] \quad (= \tfrac{1}{\ell . f})$$

```
MQA: QUADRUPOLE, L=3.3, K1 =k1;
```

Example: Definition of strength of the elements

- **Sextupole magnet**

$$k_2 = \frac{1}{p/c}\frac{\partial^2 B_y}{\partial x^2}[T/m^2]$$

```
KLSF = k2;
MSXF: SEXTUPOLE, L=1.1, K2 = KLSF;
```

- **Octupole magnet**

$$k_3 = \frac{1}{p/c}\frac{\partial^3 B_y}{\partial x^3}[T/m^3]$$

```
KLOF = k3;
MOF: OCTUPOLE, L=1.1, K3 = KLOF;
```

Example: Definition of machine elements

- **LHC dipole magnet**

```
length = 14.3;
B = 8.33;
PTOP = 7.0E12;
ANGLHC = B*clight*length/PTOP;
MBLHC: SBEND, L=length, ANGLE = anglhc;
```

```
ANGLHC = 2*pi/1232;
MBLHC: SBEND, L=length, ANGLE = anglhc;
```

Let's Try

```
      > madx
X: ==> length = 14.3;
X: ==> B = 8.33;
X: ==> PTOP = 7.0E12;
X: ==> ANGLHC = B*clight*length/PTOP;
X: ==> MBLHC: SBEND, L = LENGTH, ANGLE = ANGLHC;
X: ==> value, mblhc->angle;
```

Thick and Thin Elements

- **Thick elements:** So far examples were thick elements (or lenses)
- Specify length and strength
    - +More precise, path lengths and fringe fields
    - –Not symplectic in tracking (energy and emittance is not exactly conserved).

Thick and Thin Elements

- **Thin elements:** Specified as elements with zero length
- Specified field integration (k_0.L, k_1.L, k_2.L, ...):
    + Easy to use
    + Uses amplitude dependent kicks -> always "symplectic"
    + Used for tracking
    – Path lengths are not precise
    – Fringe fields are not precise
    – Maybe problematic for small machines

Thick and Thin Elements

Special MADX element: multipoles

- **Multipole:** General element of zero length, can be used one or more components of any order:

multip: multipole, knl := {k_{n0}L, k_{n1}L, k_{n2}L, k_{n3}L, ...};

---> knl = k_n . L (components of nth order)

- **Very simple to use**

mul1: multipole, knl := {0, k_1L, 0, 0, ...};
(is equivalent of definition of a quadrupole)

mul0: multipole, knl := {angle, 0, 0, ...};
(is equivalent of definition of a dipole)

Thick and Thin Elements

- All exercises in this course will be with thin lenses

```
my_dipol: multipole, knl := {angle, 0, 0, ...};
my_quad: multipole, knl := {0, k1L, 0, ...};
```

Definition of Sequence

- Positions of the elements are defined in a **"sequence"** file with their names
- A position can be defined at the **centre**, **exit** or **entrance** of an element
- can be defined as absolute or relative numbers

```
ciwinter_sps: SEQUENCE, REFER=CENTRE,
L=6912;

...

...

ENDSEQUENCE;
```

position of all elements in the sequence are defined here.

Definition of Sequence

```
cassps: SEQUENCE, refer=centre, l=6912; ...
...
MBL01: MBLA, at = 102.7484;

MBL02: MBLB, at = 112.7484;
MQ01: MQA, at = 119.3984;
BPM01: BPM, at = 1.75, from MQ01;
COR01: MCV01, at = LMCV/2 + LBPM/2

MBL03: MBLA, at = 126.3484;
MBL04: MBLB, at = 136.3484;
MQ02: MQB, at = 142.9984;
BPM02: BPM, at = 1.75, from MQ02;
COR02: MCV02, at = LMCV/2 + LBPM/2, from BPM02; ...

...

ENDSEQUENCE;
```

Definition of Sequence

A snippet from the SPS sequence

```
SPS : SEQUENCE,          L = 6911.5038;

 BEGI.10010       : STARTSPS    , AT = 0;
 QF.10010         : QF          , AT = 1.5425      , SLOT_ID = 2361953;
 MBA.10030        : MBA         , AT = 6.575       , SLOT_ID = 2361954;
 MBA.10050        : MBA         , AT = 13.235      , SLOT_ID = 2361955;
 MBB.10070        : MBB         , AT = 19.885      , SLOT_ID = 2361956;
 MBB.10090        : MBB         , AT = 26.525      , SLOT_ID = 2361957;
 VVSA.10101       : VVSA        , AT = 29.9385     , SLOT_ID = 2361958;

 ...

 ...

 MBA.63570        : MBA         , AT = 6899.3611   , SLOT_ID = 2363841;
 MBA.63590        : MBA         , AT = 6906.0211   , SLOT_ID = 2363842;
 LOE.63602        : LOE         , AT = 6909.8401   , SLOT_ID = 2363843;
 LSF.63605        : LSF         , AT = 6910.5088   , SLOT_ID = 2363844;
 MDH.63607        : MDH         , AT = 6910.9838   , SLOT_ID = 2363845;
 BPH.63608        : BPH         , AT = 6911.2713   , SLOT_ID = 2363846;
 END.10010        : ENDOFSPS    , AT = 6911.5038;
ENDSEQUENCE;
```

Definition of Sequence

```
circum = 6912;

// bending magnets as thin lenses
mbsps: multipole,knl={0.007272205};

// quadrupoles and sextupoles
qf: quadrupole,l=3.085,k1 =  0.0146315;
qd: quadrupole,l=3.085,k1 = -0.0146434;
lsf: sextupole,l=1.0,  k2 =  1.9518486E-02;
lsd: sextupole,l=1.0,  k2 = -3.7618842E-02;

// monitors and orbit correctors
bpm: monitor,l=0.1;
ch:  hkicker,l=0.1;
cv:  vkicker,l=0.1;
```

Definition of Sequence

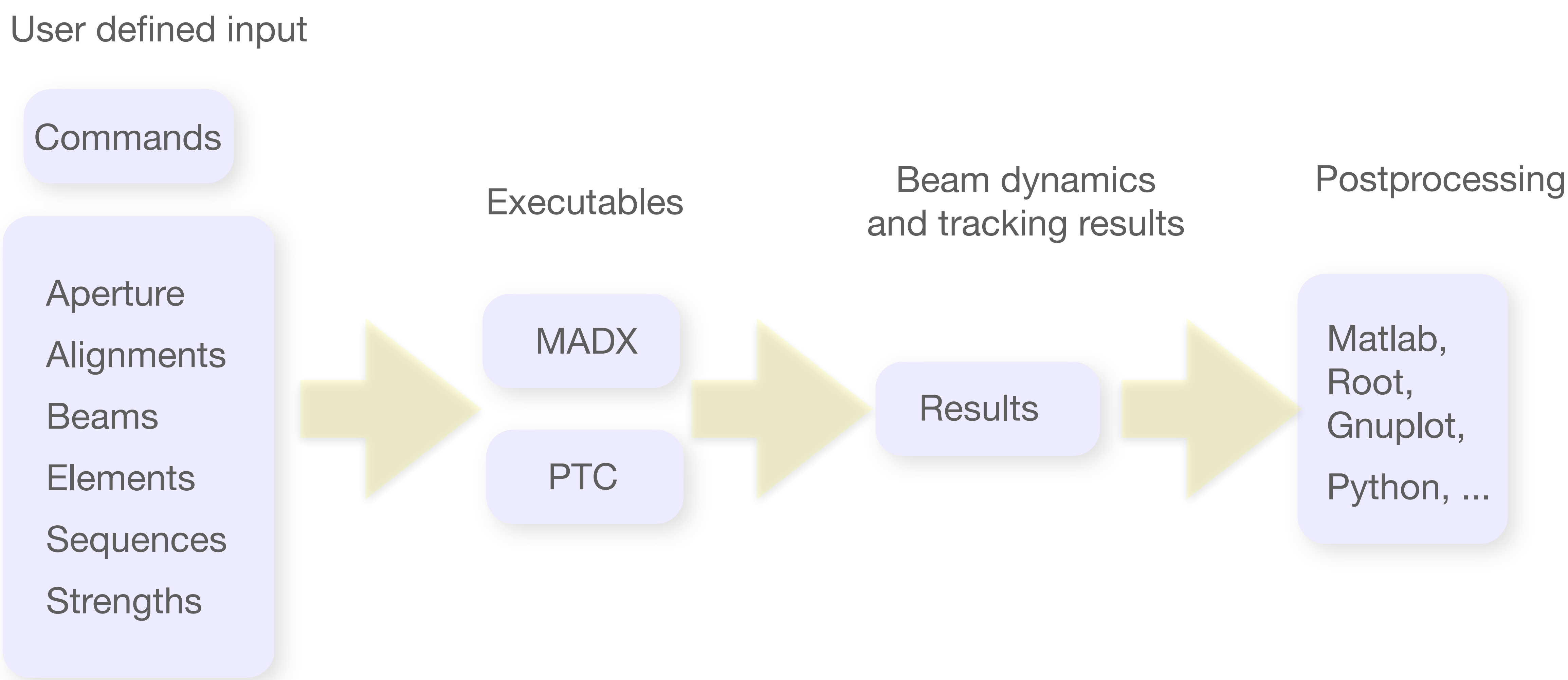
```
cassps: sequence, l = circum;
start_machine: marker, at = 0;
qf,  at = 1.5425;
lsf, at = 3.6425;
ch,  at = 4.2425;
bpm, at = 4.3425;
mbsps, at = 5.0425;
mbsps, at = 11.4425;
mbsps, at = 23.6425;
mbsps, at = 30.0425;
qd, at = 33.5425;
lsd, at = 35.6425;
cv,  at = 36.2425;
bpm, at = 36.3425;
...

...

mbsps, at = 6903.6425;
mbsps, at = 6910.0425;
end_machine: marker, at = 6912;
endsequence;
```

Definition of Sequence

```
circum=6912.0; // define the total length
ncell = 108; // define number of cells
lcell = circum/ncell;
// all magnets as multipoles
mbsps: multipole, knl={2.0*pi/(2*ncell)};
qfsps: multipole, knl={0.0, 4.36588E-02};
qdsps: multipole, knl={0.0,-4.36952E-02};
// sequence declaration;
cassps: sequence, refer=centre, l=circum;
   n = 1;
   while (n <= ncell) {
   qfsps: qfsps,   at=(n-1)*lcell;
   mbsps: mbsps,   at=(n-1)*lcell+16.0;
   qdsps: qdsps,   at=(n-1)*lcell+32.00;
   mbsps: mbsps,   at=(n-1)*lcell+48.00;
   n = n + 1;
}
endsequence;
```

SPS sequence, elements in a loop

MADX and post-processing flow chart



Example case

```
TITLE, 'MAD-X Test';

// Read the lattice from the sequence file.
call file="sps.seq";
option,-echo,-thin_foc;

// Define the beam.
Beam, particle = proton, sequence=ci_sps, energy = 450.0;

// Read the sequence called ci_sps.
use, sequence=ci_sps;

// Select the parameters to be calculated.
select,flag=twiss,column=name,s,betx,bety;

// Run TWISS command to calculate the Twiss parameters.
// Calculate parameters in the centre of the elements
// and write the results in twiss.out file.
twiss,save,centre,file=twiss.out;

// Plot the horizontal and vertical dispersion
// between 10th and 16th defocusing quadrupole.

plot, haxis=s, vaxis=betx, bety,colour=100,range=qd[10]/qd[16];
plot, haxis=s, vaxis=dx, colour=100,range=qd[10]/qd[16];

survey,file=survey.out;

stop;
```

Example case

```
TITLE, 'MAD-X Test';

// Read the lattice from the sequence file.
call file="sps.seq";
option,-echo,-thin_foc;

// Define the beam.
Beam, particle = proton, sequence=hpfbu_sps, energy = 450.0;

// Read the sequence called ci_sps.
use, sequence=ci_sps;

// Select
select,fl

// Run Tw
// Calcul
// and wr
twiss,sav

// Plot t
// betwee

plot, hax
plot, hax

survey,file=survey.out;

stop;
```

- **Call the sequence file defining the machine**
  - call, file="sps.seq";

```
TITLE, 'MAD-X Test';

// Read the lattice from the sequence file.
call file="sps.seq";
option,-echo,-thin_foc;

// Define the beam.
Beam, particle = proton, sequence=ci_sps, energy = 450.0;

// Read the sequence called ci_sps.
use, sequence=ci_sps;

// Select
select,fla

// Run TWI
// Calcula
// and wri
twiss,save

// Plot th
// between 10th and 16th defocusing quadrupole.

plot, haxis=s, vaxis=betx, bety,colour=100,range=qd[10]/qd[16];
plot, haxis=s, vaxis=dx, colour=100,range=qd[10]/qd[16];

survey,file=survey.out;

stop;
```

- **Define beam type and properties**

```
TITLE, 'MAD-X Test';

// Read the lattice from the sequence file.
call file="sps.seq";
option,-echo,-thin_foc;

// Define the beam.
Beam, particle = proton, sequence=ci_sps, energy = 450.0;

// Read the sequence called ci_sps.
use, sequence=ci_sps;

// Select the parameters to be calculated.
select,flag=twiss,column=name,s,betx,bety;

// Run TWI
// Calcula
// and wri
twiss,save

// Plot th
// between

plot, haxi
plot, haxi

survey,file

stop;
```

- **Activate your machine by "using" the sequence**
  - USE, sequence = ci_sps;
  - There can be other sequences in "sps.seq"
  - USE command activates the sequence named

Example case

```
TITLE, 'MAD-X Test';

// Read the lattice from the sequence file.
call file="sps.seq";
option,-echo,-thin_foc;

// Define the beam.
Beam, particle = proton, sequence=ci_sps, energy = 450.0;

// Read the sequence called ci_sps.
use, sequence=ci_sps;

// Select the parameters to be calculated.
select,flag=twiss,column=name,s,betx,bety;

// Run TWISS command to calculate the Twiss parameters.
// Calculate parameters
// and write the results
twiss,save,centre,file=t

// Plot the horizontal a
// between 10th and 16th

plot, haxis=s, vaxis=bet
plot, haxis=s, vaxis=dx,

survey,file=survey.out;

stop;
```

- **SELECT the parameters to work with for**
  - Calculating of the Twiss parameter
  - Saving the lattice functions
  - Plotting
  - …

```
TITLE, 'MAD-X Test';

// Read the lattice from the sequence file.
call file="sps.seq";
option,-echo,-thin_foc;

// Define the beam.
Beam, particle = proton, sequence=ci_sps, energy = 450.0;

// Read the sequence called ci_sps.
use, sequence=ci_sps;

// Select the parameters to be calculated.
select,flag=twiss,column=name,s,betx,bety;

// Run TWISS command to calculate the Twiss parameters.
// Calculate parameters in the centre of the elements
// and write the results in twiss.out file.
twiss,save,centre,file=twiss.out;

// Plot the horizontal and vertical dispers
// between 10th and 16th defocusing quadru

plot, haxis=s, vaxis=betx, bety,colour=100,
plot, haxis=s, vaxis=dx, colour=100,range=

survey,file=survey.out;

stop;
```

- **Start the calculation**
  - **twiss;** or
  - **twiss, file=output;** or
  - **twiss, sequence=hpfbu_sps;**

Example case

```
TITLE, 'MAD-X Test';

// Read the lattice from the sequence file.
call file="sps.seq";
option,-echo,-thin_foc;

// Define the beam.
Beam, particle = proton, sequence=ci_sps, energy = 450.0;

// Read the sequence called ci_sps.
use, sequence=ci_sps;

// Select the parameters to be calculated.
select,flag=twiss,column=name,s,betx,bety;

// Run TWISS command to ca
// Calculate parameters in
// and write the results i
twiss,save,centre,file=twi

// Plot the horizontal and vertical dispersion
// between 10th and 16th defocusing quadrupole.

plot, haxis=s, vaxis=betx, bety,colour=100,range=qd[10]/qd[16];
plot, haxis=s, vaxis=dx, colour=100,range=qd[10]/qd[16];

survey,file=survey.out;

stop;
```

- **Plot beta and dispersion functions**

```
TITLE, 'MAD-X Test';

// Read the lattice from the sequence file.
call file="sps.seq";
option,-echo,-thin_foc;

// Define the beam.
Beam, particle = proton, sequence=ci_sps, energy = 450.0;

// Read the sequence called ci_sps.
use, sequence=ci_sps;

// Select the parameters to be calculated.
select,flag=twiss,column=name,s,betx,bety;

// Run TWISS command to calculate the Twiss parameters.
// Calculate parameters in the centre of the elements
// and write the results in twiss.out file.
twiss,save,centre,file=twi

// Plot the horizontal anc
// between 10th and 16th c

plot, haxis=s, vaxis=betx, bety,colour=100,range=qd[10]/qd[16];
plot, haxis=s, vaxis=dx, colour=100,range=qd[10]/qd[16];

survey,file=survey.out;

stop;
```

- **Survey the geometry of the orbit. Is it closed?**

MADX results on your command line

```
++++++ table: summm

       length          orbit5             alfa          gammatr
         6912              -0   0.001504942753      25.77745337

           q1             dq1          betxmax            dxmax
  26.57999204     -1.67838253      108.7763569       2.44661758

        dxrms          xcomax           xcorms               q2
  1.830638952               0                0      26.62004577

          dq2         betymax            dymax            dyrms
 -1.680294089     108.7331749                0                0

       ycomax          ycorms           deltap          synch_1
            0               0                0                0

      synch_2         synch_3          synch_4          synch_5
            0               0                0                0
```

Example case

Header part of an example output file

```
@ NAME             %05s "TWISS"
@ TYPE             %05s "TWISS"
@ SEQUENCE         %09s "HPFBU_SPS"
@ PARTICLE         %06s "PROTON"
@ MASS             %le        0.938272013
@ CHARGE           %le                  1
@ ENERGY           %le                450
@ PC               %le        449.9990218
@ GAMMA            %le        479.6050546
@ KBUNCH           %le                  1
@ BCURRENT         %le                  0
@ SIGE             %le                  0
@ SIGT             %le                  0
@ NPART            %le                  0
@ EX               %le                  1
@ EY               %le                  1
@ ET               %le                  1
@ LENGTH           %le               6912
@ ALFA             %le     0.001504942753
@ ORBIT5           %le                 -0
@ GAMMATR          %le        25.77745337
@ Q1               %le        26.57999204
@ Q2               %le        26.62004577
@ DQ1              %le        -1.67838253
@ DQ2              %le       -1.680294089
@ DXMAX            %le         2.44661758
@ DYMAX            %le                  0
@ XCOMAX           %le                  0
@ YCOMAX           %le                  0
@ BETXMAX          %le        108.7763569
```

- twiss.out output file is created after running the input file with "madx" extension.

1

```
* NAME                              S            BETX            BETY
$ %s                              %le             %le             %le
 "HPFBU_SPS$START"                  0     101.5961579     20.70328425
 "START_MACHINE"                    0     101.5961579     20.70328425
 "DRIFT_0"                    0.77125     105.1499566     19.94571028
 "QF"                          1.5425     108.7763569     19.26082066
 "DRIFT_1"                     2.5925     103.8571423     20.21112973
 "LSF"                         3.6425     99.07249356     21.29615787
 "DRIFT_2"                  3.9424975     97.73017837      21.6309074
 "CH"                          4.2425     96.39882586     21.97666007
 "DRIFT_3"                     4.2925     96.17800362     22.03535424
 "BPM"                         4.3425     95.95748651      22.0943539
 "DRIFT_4"                  4.6925025      94.4223997     22.51590816
 "MBSPS"                       5.0425     92.90228648     22.95242507
 "DRIFT_5"                     8.2425     79.69728195     27.63752778
 "MBSPS"                      11.4425     67.74212222      33.5738988
 "DRIFT_6"                    17.5425     48.41469349     48.35614376
 "MBSPS"                      23.6425      33.6289371     67.68523387
 "DRIFT_5"                    26.8425     27.68865546      79.6433337
 "MBSPS"                      30.0425     22.99821861     92.85270185
 "DRIFT_7"                    31.7925     20.96178735     100.6058286
 "QD"                         33.5425     19.29915001     108.7331749
 "DRIFT_1"                    34.5925     20.25187715     103.8118608
```

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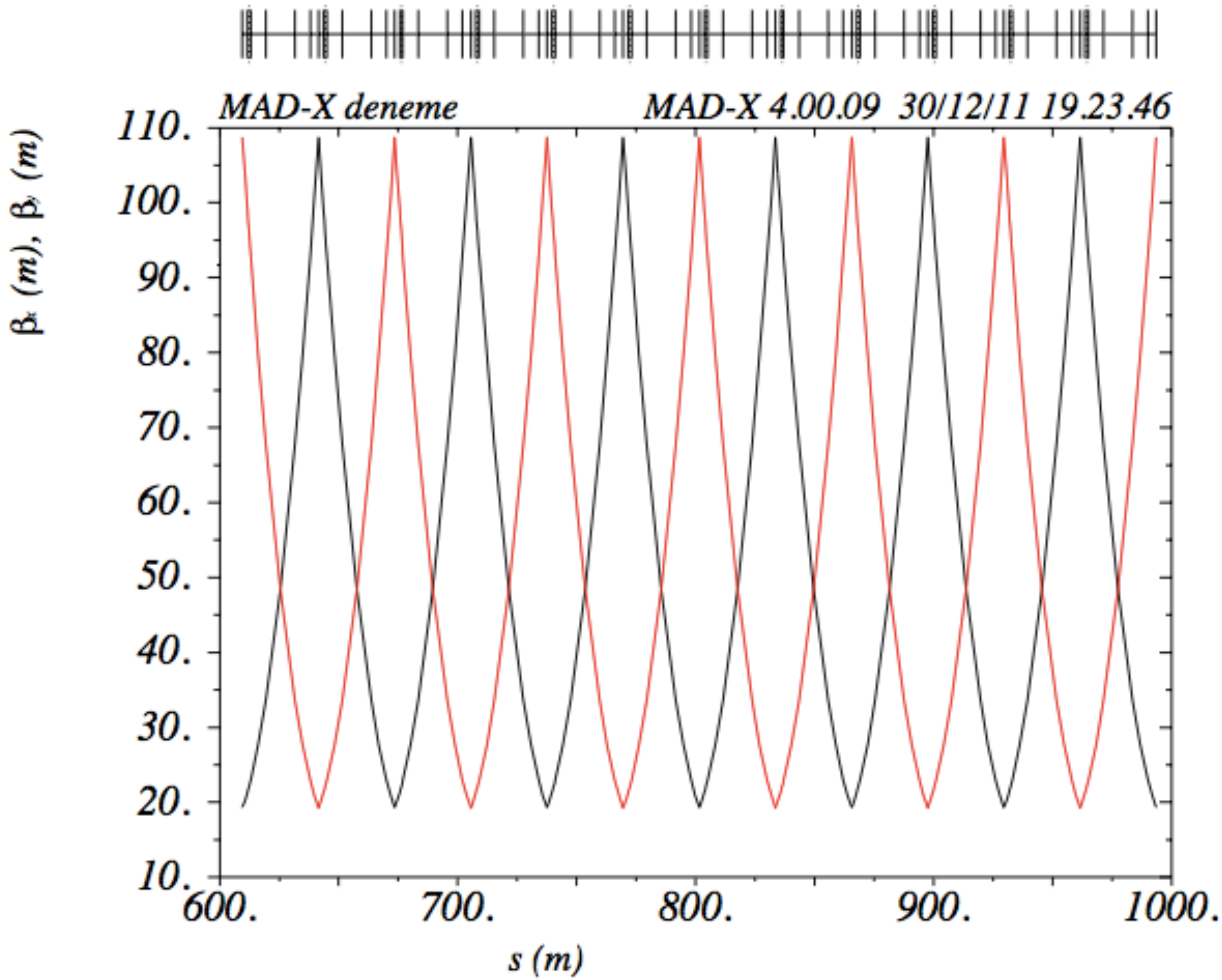
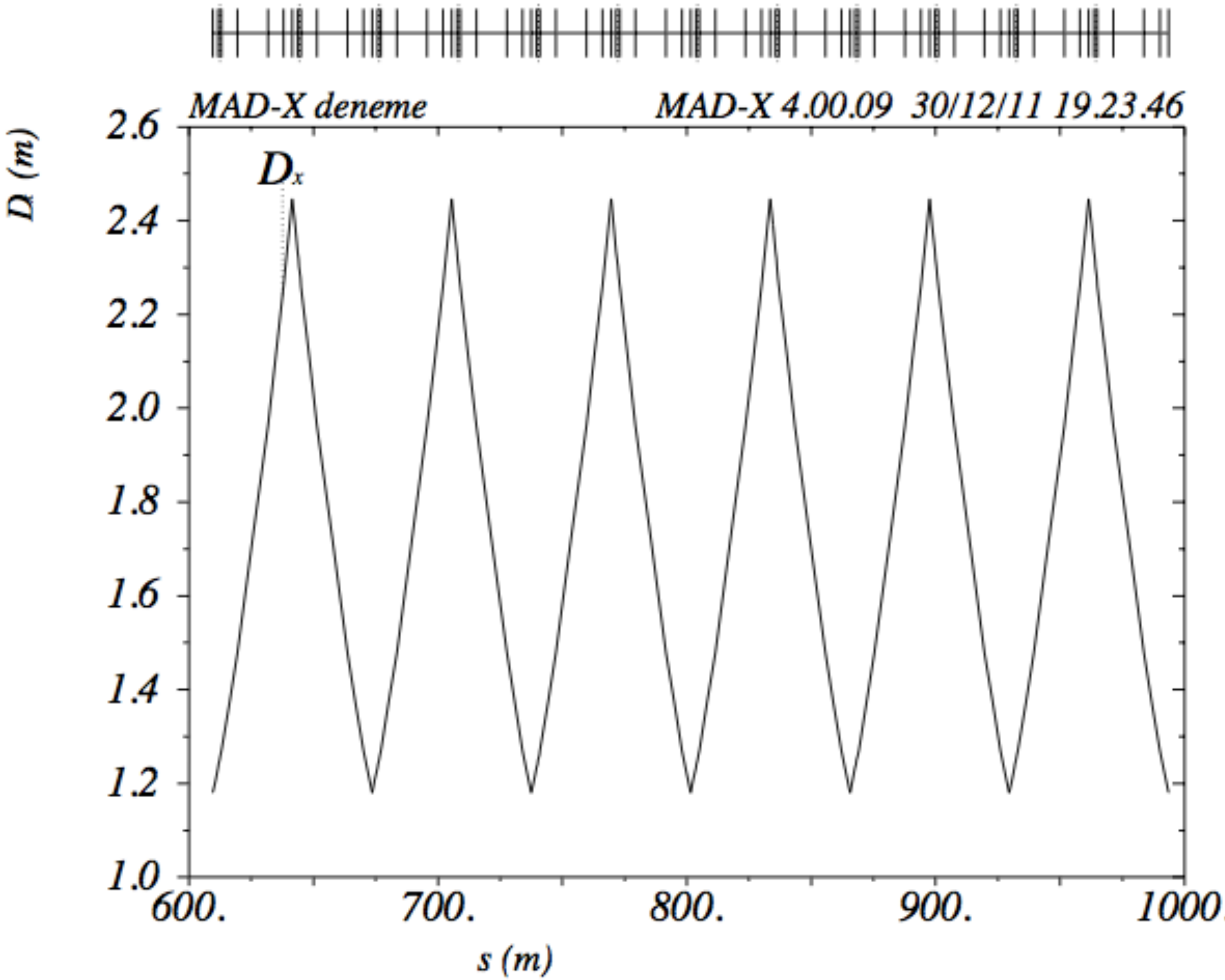
MADX graphical output: Beta functions

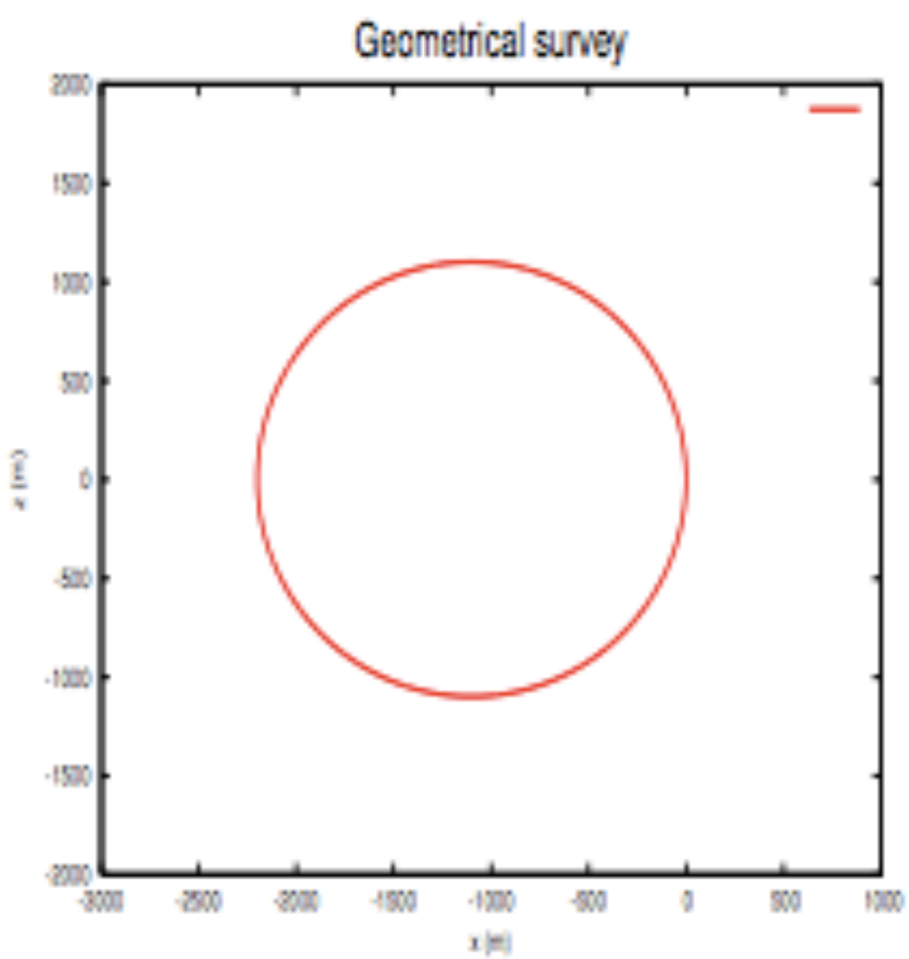


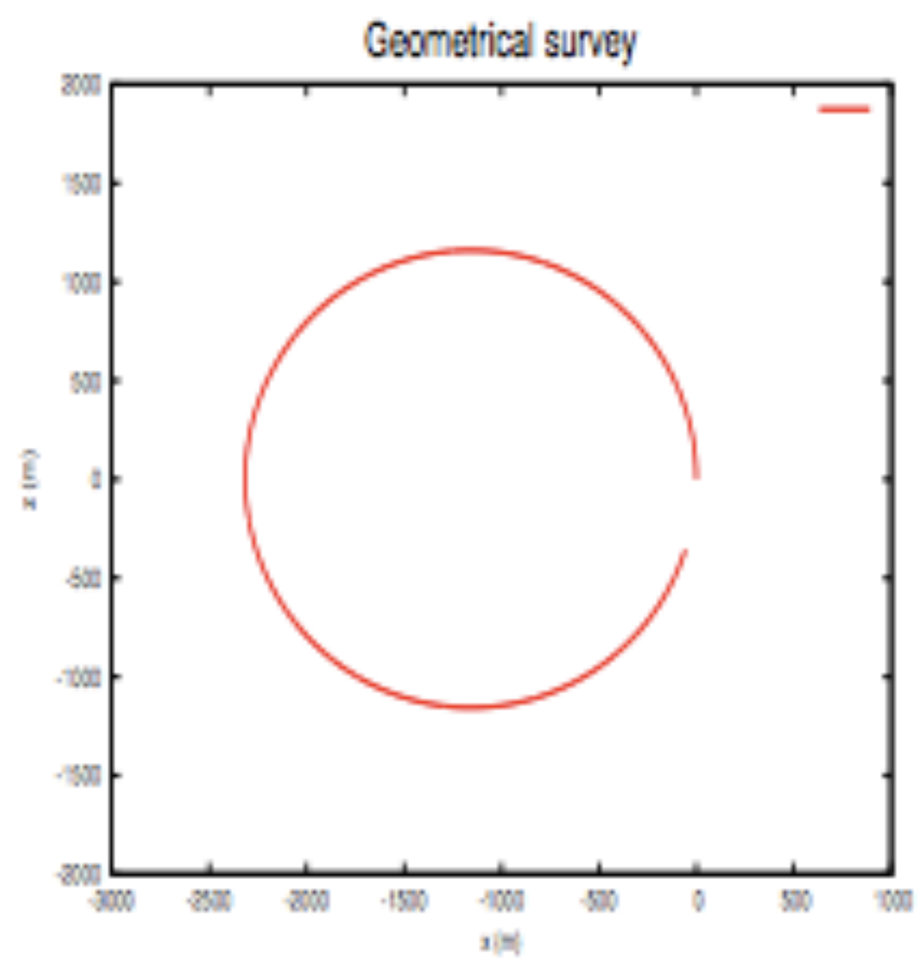
MADX graphical output: Dispersion function



MADX graphical output: Survey

- Output gives x, y, z and theta
- Plot x as a function of z to survey the close orbit.





Optical Matching

Main applications:

- **Setting global optical parameters:**
  (tune, chromaticity ...)

- **Setting local optical parameters**
  (beta function, dispersion ...)

- **Orbit correction**

Global Matching

- Adjust respective multipole strengths to get desired parameters
- Define the properties required and the elements to vary.
- Examples for global parameters:
  - Q1, Q2: Horizontal and vertical tune.
  - dQ1, dQ2: Horizontal and vertical chromaticity.

Global Matching

- Match horizontal (Q1) and vertical (Q2) tunes.
- Vary the quadrupole strengths (kqf, kqd).

```
match, sequence=hpfbu_sps;
   vary,name=kqf, step=0.00001;             → to vary
   vary,name=kqd, step=0.00001;             → to vary
   global,sequence=hpfbu_sps,Q1=26.58;      → target value
   global,sequence=hpfbu_sps,Q2=26.62;      → target value
   Lmdif, calls=10, tolerance=1.0e-21;
endmatch;
```

sps_matching.madx