CAS Course on Optics Design

Otwock, September 2015

Information at:
http://cern.ch/Werner.Herr/CAS2015_COURSE

CAS 2015 course on optics design

- Aims:
  - From the lectures to praxis
  - Design a realistic machine optics with various features
- Not a lecture, but following a series of steps (as exercises) applying what was learned in previous lectures
- Done by you in close collaboration with the tutors and your colleagues (this is
- The MADX program is used for this course

Procedure and basic steps

- Introduction to MAD-X (2 talks)
- Work on 8 exercises:
  - Design of periodic machine with desired properties (1-2)
  - Correction of chromaticity and orbit imperfections (3-5)
  - Design of a dispersion suppressor (6)
  - Design of a β-insertion (low and high β, for experiments, collimation etc.) (7)
  - Particle tracking to study stability of your design (8)

Available tools

- Individual computers
- LINUX operating system
- You have MAD-X, compilers, gnuplot ...

  - Bonus material:
    You get all <u>your</u> solutions and <u>our</u> suggested solutions together with the MAD-X binaries after the school.

Available to help

Werner Herr,
Guido Sterbini,
Bernhard Holzer (week 1),
Verena Kain,
Yannis Papaphilippou

for computers: Adam Wasilewski, Jacek Szlachciak

How to get in ?

- For LINUX: see instructions or ask for help
- Common accounts:

  login name: user

  password: xxxxxxxx

  (always use the same computer, files are local)
- If you want to use your own computer, download MADX from website:
  - WINDOWS: http://cern.ch/Werner.Herr/CAS2015_COURSE/exe
  - LINUX: http://cern.ch/Werner.Herr/CAS2015_COURSE/bin

Where you find all that:

You find a directory: **/home/user/COURSE** **on your machine**
(You may have it as a .tar file, extract with e.g.: tar xvf *name*)

Documentation: **/COURSE/doc**

Your exercises in: **/COURSE/doc/problems.pdf**

Examples in: **/COURSE/examples**

Solutions at: **/COURSE/solutions**

Executable:
/COURSE/bin/madx (LINUX, may have to set PATH)
(e.g.: setenv PATH "$PATH":"*pathname*")

Introduction to MADX

Werner Herr, CERN

For all MAD details:

(http://cern.ch/mad)

see also:

MADX primer

MADX - part 1 (today)

- Description of the basic concepts and the language
- Define a machine and compute optical functions
- Get the parameters you want
  - Beam dimensions
  - Tune, chromaticity

Required lectures: Recap transverse dynamics, Lattice cells

MADX - part 2 (as we progress ..)

- Machines with imperfections and corrections
  - Closed Orbit distortions and correction
- Design of insertions
  - Dispersion suppressor
  - Low β insertion
- Particle tracking

Required lectures: Recap Transverse Dynamics, Lattice cells, Insertions, Non-linear dynamics

General purpose lattice programs

- For circular machines, beam lines or linacs
- Calculate optics parameters from machine description
- Compute (match) desired quantities
- Simulate and correct machine imperfections
- Simulate beam dynamics

→ Used in this course: MADX

What is MADX ?

- The latest version in a long line of development

  (Methodical Accelerator Design)
- Used at CERN since more than 30 years for machine design and simulation (PS, SPS, LEP, LHC, ..)
- Existing versions:
  MAD8 (obsolete), MADX (version 5)
- Mainly designed for large projects (LEP, LHC*) , CLIC ..)

*) Only MADX can handle the LHC ...

Why we use MADX here ?

- Multi purpose:
  - From early design to final evaluation
  - Running on all systems, Source is free and easy to extend
- Easy to understand what is happening:
  - Well defined strategy for input language
  - No hidden or invisible actions or computations
- Other programs also used somewhere else:
  - SAD (KEK: Strategic Accelerator Design)
  - BMAD (Cornell)

Data required by all optics programs ?

- Description of the machine:
  - Definition of each machine element:
    e.g. a focusing quadrupole
  - Attributes of the elements:
    e.g. 3.1 m long and my gradient is k_1
  - Positions of the elements:
    e.g. 2341 m from the beginning
- Description of the beam(s):
  Protons at 7 TeV
- Directives (what to do ?):
  Give me optical functions, match the optics

How does MAD get and use this information ?

- MAD is an "interpreter":

  MAD prompt is: X: ==>

  - Accepts and (immediately) executes statements
  - Statements can be assignments, expressions or initiate complex actions (commands)
  - Can be used interactively or in batch
    - Reads statements from input stream or a file (has no GUI)
- Many features of a programming language (loops, if conditions, macros, subroutines ...)

MAD input language

Strong resemblance to "C" language

- Not line oriented, all statements are terminated by ;
- Comment lines start with: // or !
- Arithmetic expressions, including functions (exp, log, sin, cosh ...)
- Immediate (=) and deferred expressions (:=) (like JAVA)
- In-built random number generators for various distributions
- Predefined constants (clight, e, π, m$_p$, m$_e$ ...)

MADX conventions

- Not case sensitive
- Elements 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
  - i.e. x = y = 0 follows the curvilinear system (reference orbit)

Examples of expressions:

- Variables can be used in expressions:
  - ANGLE = 2*PI/NBEND;
  - AIP = ATAN(SX1/SX2);
- The assignment symbols = and := have a very different behaviour (here random number generator)!
  - DX = GAUSS()*1.5E-3;
    The value is computed once and kept in DX
  - DX := GAUSS()*1.5E-3;
    The value is recomputed every time DX is used

How to use MADX ?

```
$ madx
X: ==> angle = 2*pi/1232;
X: ==> value, angle;
X: ==> dx = gauss()*2.0;
X: ==> value, dx;
X: ==> value, dx;
X: ==> dx := gauss()*2.0;
X: ==> value, dx;
X: ==> value, dx;
```

How to use MADX ?

Fore a large machine you may need many commands (LHC $\approx$ 27000)
Better: store your input in a file: e.g. my.file

```
$ madx
X: ==> call, file=my.file; (WINDOWS or LINUX)
```

alternatively, redirection from the file into the parser (LINUX)

```
$ madx < my.file (LINUX)
```

⚠ Warning ! ⚠

- For WINDOWS users:
  - The input file must be a plain text (ASCII) file !
  - NOT a WORD, POWERPOINT or EXCEL file ...
- For ALL users:
  - Do NOT use colours in the commands (I use them only here for the talk !)

MAD input statements (what we need)

- Typical assignments:
  - Properties of machine elements
  - Set up of the lattice
  - Definition of beam properties (particle type, energy, emittance ...)
- Typical actions:
  - Compute lattice functions, match optical parameters
  - Assignment of errors and imperfections
  - Correct machines

Recommendation: make use of the examples !

How to define machine elements ?

- MAD-X Keywords used to define the type of an element.
- General format:
  - $name : keyword, attributes;$
- Can define single *element* or *class* of elements and give it a name of your choice

→ Some keywords are predefined, name can be anything (but avoid blanks in the name)

→ Some examples:

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Example: Definitions of magnets

Dipole (bending) magnet:

$$k_0 \;=\; \frac{1}{p/c} B_y \,[\; in \quad m^{-1}\;] \left[\; = \; \frac{1}{\rho} \; = \; \frac{angle}{l} \right] [\; in \quad rad/m\;]$$

$$\underbrace{DIP01}_{name} : \underbrace{SBEND}_{keyword}, \underbrace{L = 10.0, ANGLE = angle, K0 = k_0;}_{attributes}$$

Quadrupole magnet:

$$k_1 \;=\; \frac{1}{p/c} \frac{\partial B_y}{\partial x} [\; in \quad m^{-2}\;] \left[\; = \; \frac{1}{l \cdot f} \right]$$

$$MQA : QUADRUPOLE, L = 3.3, K1 = k_1;$$

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Example: Definitions of magnets

Sextupole magnet:

$$k_2 \; = \; \frac{1}{p/c} \frac{\partial^2 B_y}{\partial x^2} [\; in \quad m^{-3} \;]$$

KLSF $= k_2$;
MSXF: SEXTUPOLE, L=1.1, K2 = KLSF;

Octupole magnet:

$$k_3 \; = \; \frac{1}{p/c} \frac{\partial^3 B_y}{\partial x^3} [\; in \quad m^{-4} \;]$$

KLOF $= k_3$;
MOF: OCTUPOLE, L=1.1, K3 = KLOF;

Other elements:

Drift space:

DR1: DRifT, L=1.1;

Marker (has no effect, mostly used as a position reference):

MK1: Marker;

Example: definitions of elements

Define a class of Quadrupole magnets:

MQF: QUADRUPOLE, L=3.3, K1 = +1.23E-02;
MQD: QUADRUPOLE, L=3.3, K1 = -1.23E-02;

QUAD01, QUAD02, ... are instances of the class MQF etc., all with the same properties:

QUAD01: MQF;
QUAD02: MQD;
QUAD03: MQF;
QUAD04: MQD;
....

Example: LHC dipole magnet

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

the same example for other codes (for comparison):
BMAD $\rightarrow$ MBLHC: SBEND, L = Length, ANGLE = anglhc
SAD $\rightarrow$ SBEND MBLHC =(L = Length ANGLE = anglhc)

Try it ..

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

Thick and thin elements

- Thick elements: so far all examples were thick elements (or: lenses)
- Specify length and strength separately (except dipoles !)
  - + More precise, path lengths and fringe fields correct
  - − Not symplectic in tracking
  - − May need symplectic integration

- Thin elements: specified as elements of zero length
- Specify field integral, e.g.: $k_0 \cdot L,\ k_1 \cdot L,\ k_2 \cdot L, ...$
  - + Easy to use
  - + Used for tracking
  - − Path lengths not correctly described
  - − Fringe fields not correctly described
  - − Maybe problematic for small machines

For a proper discussion see lecture on "Tools for Non-Linear Dynamics"

Special MAD element: multipoles

Multipole: general element of zero length (thin lens), can be used with one or more components of any order:

multip: multipole, knl := $\{$k$_{n0}$L, k$_{n1}$L, k$_{n2}$L, k$_{n3}$L, ...$\}$;

$\rightarrow$ knl $= k_n \cdot L$ (normal components of nth order)

Very simple to use:

mul1: multipole, knl := $\{$0,k$_1$L,0,0,....$\}$;
is equivalent to definition of quadrupole (k$_1$L $= \int \frac{1}{p/c}\frac{\partial B_y}{\partial x} \cdot dl$)

mul0: multipole, knl = $\{$angle,0,0,....$\}$;
is equivalent to definition of a dipole (k$_0$L = angle)

Thick and thin elements

- For all exercises: → use thin lenses (multipoles) unless explicitly requested to use thick elements
- Easier to handle and analytic calculations are precise

E.g. for a dipole you can use:

MYD: MULTIPOLE, KNL = {angle,0,0,....};

E.g. for a quadrupole with an octupole component you can use:

MYQ: MULTIPOLE, KNL := {0,k_1L,0,k_3L,0,....};

Definitions of sequence (position)

Have to assign position to the elements.
Positions are defined within a sequence with a name:

```
cassps: SEQUENCE, REFER=CENTRE, L=6912;
...
          here specify positions of all elements ...
...
ENDSEQUENCE;
```

A (relative (to some other element) or absolute) position can be defined.

General format is:
name: at = (position s in metres);

or (if an element appears several times):
name: class, at = (position s in metres);

Definitions of sequence (position)

```
cassps: SEQUENCE, refer=centre, l=6912;
...
...
MBL01:  MBLA,   at = 102.7484; ! absolute position
MBL02:  MBLB,   at = 112.7484;
MQ01:  MQA,   at = 119.3984;
BPM01:  BPM,   at = 1.75, from MQ01; ! relative position
COR01:   at = LMCV/2 + LBPM/2, from BPM01;
MBL03:  MBLA,   at = 126.3484;
MBL04:  MBLB,   at = 136.3484;
MQ02:  MQB,   at = 142.9984;
BPM02:  BPM,   at = 1.75, from MQ02;
COR02:   at = LMCV/2 + LBPM/2, from BPM02;
...
...
ENDSEQUENCE;
```

Complete example: SPS (thick)

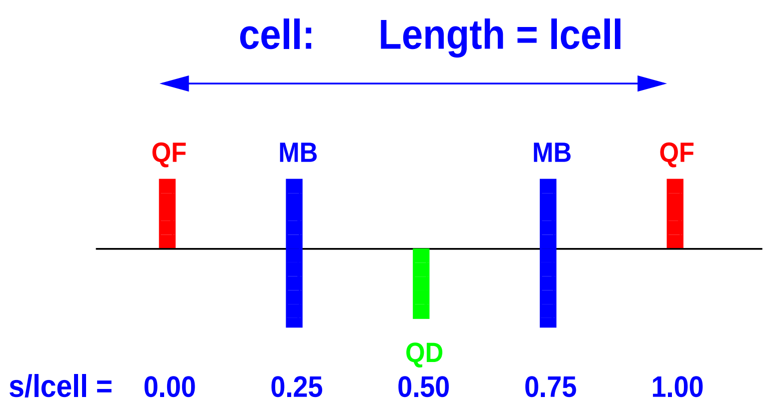
```
circum = 6912;
// bending magnets as thin lenses
mbsps: multipole,knl={0.007272205};

// quadrupoles and sextupoles
kqf =  0.0146315;
kqd = -0.0146434;
qfsps: quadrupole,l=3.085,k1 := kqf;
qdsps: quadrupole,l=3.085,k1 := kqd;
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;

cassps: sequence, l = circum;
start_machine: marker, at = 0;
qfsps,  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;
qdsps, at = 33.5425;
lsd, at = 35.6425;
cv,  at = 36.2425;
bpm, at = 36.3425;
....
....
qdsps, at = 6881.5425;
lsd, at = 6883.6425;
cv,  at = 6884.2425;
bpm, at = 6884.3425;
mbsps, at = 6885.0425;
mbsps, at = 6891.4425;
mbsps, at = 6903.6425;
mbsps, at = 6910.0425;
end_machine: marker, at = 6912;
endsequence;
```

Definition of large machines ...

- For large machines with many elements:
  - Time consuming to specify every element individually (e.g. LHC more than 25000 elements needed)
  - Very inflexible (e.g. change of cell length)
- Several options:
  - Loops over elements possible
  - Elements can be combined into new objects

A very simple cell ..



A very simple cell ..

- Positions can be defined in loops:
- Loop over number of cells ($ncell$)

```
lcell = 64;     ! cell length
ncell = 108;     ! number of cells
circum = ncell*lcell;     ! total circumference
cassps:  sequence, refer=centre, l=circum;
   n = 1;
   while (n < ncell+1) {
      qfsps:  qfsps, at=(n-1)*lcell;
      mbsps:  mbsps, at=(n-1)*lcell + lcell*0.25;
      qdsps:  qdsps, at=(n-1)*lcell + lcell*0.50;
      mbsps:  mbsps, at=(n-1)*lcell + lcell*0.75;
      n = n + 1;
  }
endsequence;
```

We have 6 lines instead of 432 (and are much more flexible !)

Nested sequences

➡ Sequences can be defined and used like (new) elements:

```
cascell1:  sequence, refer=centre, l=lcell;   (cascell1 is now an element)
   qfsps:  qfsps, at=0.0;
   mbsps:  mbsps, at=0.25*lcell;
   qdsps:  qdsps, at=0.50*lcell;
   mbsps:  mbsps, at=0.75*lcell;
endsequence;


allcells:  sequence, refer=centre, l=ncell*lcell;
   n = 1;
   while (n < ncell+1) {
      cascell1, at=(n-1)*lcell;
      n = n + 1;
   }
endsequence;
```

Simple MAD directives

- Define the input
- Define the beam
- Initiate computations (Twiss calculation, error assignment, orbit correction etc.)
- Output results (tables, plotting)
- Match desired parameters
- Beware: may have default values !

Input definition and selection

- Define the input:
  - call,"sps.seq";
  - Selects a file with description of machine
  - Can be split into several files
- Activate the machine:
  - USE, sequence=cassps;
  - Activates the sequence you want (described in "sps.seq", which can contain more than one)

We still need a beam !

Some computations need to know the type of beam and its properties:

- Particle type
- Energy
- Emittance, number of particles, intensity ....

```
BEAM, PARTICLE=name, MASS=mass, NPART=Nb, CHARGE=q,
ENERGY=E,.......;
```

Example:

```
BEAM, PARTICLE=proton, NPART=1.1E11, ENERGY=450,.......;
```

Initiate the computations

Execute an action (calculation of all lattice parameters around the (circular !) machine):

twiss; or:
twiss, file=output; or:
twiss, file=output, sequence=cassps;

Execute an action (produce graphical output of β-functions):

plot, haxis=s, vaxis=betx, bety;

SELECT - a powerful command

Assigns parameters and options for an action, as an example twiss:

select,flag=twiss,column=name,s,betx,bety;
(defines output for action twiss: name, s, betx, bety)

Output for selected elements only, using C language regular expressions, examples:

select,flag=twiss,pattern="q.*",column=name,s,betx,bety;
shown only for elements starting with: "q"
select,flag=twiss,range="MQF01",column=name,s,betx,bety;
shown only for the element with name: "MQF01"
select,flag=twiss,range="QD[10]/QD[16]",column=name,s,betx,bety;
shown only for the elements inside the range of 10th to 16th quadrupole

Initiate the computations

Set parameters for an action with the SELECT command (or defaults are used)

Calculation of Twiss parameters around the machine, store selected lattice functions on file twiss.out and plot β-functions:

```
select,flag=twiss,column=name,s,betx,bety;
twiss, sequence=cassps, file=twiss.out;

plot, haxis=s, vaxis=betx, bety, colour=100;
```

Initiate the computations

Calculation of Twiss parameters around the machine, store and plot lattice functions for quadrupoles only (name starting with "q"):

```
select,flag=twiss,pattern="^q.*",column=name,s,betx,bety;
twiss, sequence=cassps, file=twiss.out;

plot, haxis=s, vaxis=betx, bety, colour=100;
```

Initiate the computations

Make a geometrical survey of the machine layout, available in a file:

```
select,flag=twiss,column=name,s,betx,bety;
twiss, sequence=cassps, file=twiss.out;

survey, file=survey.cas;
```

Initiate the computations

Calculation of Twiss parameters around the machine, plot between 10th and 16th quadrupoles only:

```
select,flag=twiss,pattern="^q.*",column=name,s,betx,bety;
twiss, sequence=cassps, file=twiss.out;

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

Typical MAD example input:

```
// Read input file with machine description
call file="sps.seq";

// Define the beam for the machine
Beam, particle=proton, sequence=cassps, energy=450.0;

// Use the sequence with the name: cassps
use, sequence=cassps;

// Define the type and amount of output
select,flag=twiss,column=name,s,betx,bety;

// Execute the Twiss command to calculate the Twiss parameters
// Compute at the centre of the element and write to: twiss.out
twiss,save,centre,file=twiss.out;

// Plot the horizontal and vertical beta function between the
// 10th and 16th occurence of a defocussing quadrupole
plot, haxis=s, vaxis=betx, bety,colour=100, range=qd[10]/qd[16];

// get the geometrical layout (survey)
survey,file=survey.cas;

stop;
```

Typical MAD example input:

```
// Read input file with machine description
call file="sps.seq";

// Define the beam for the machine
Beam, particle=proton, sequence=cassps, energy = 450.0;

// Use the sequence with the name: cassps
use, sequence=cassps;

// Define the type and amount of output
select,flag=twiss,column=name,s,betx,bety;

// Execute the Twiss command to calculate the Twiss parameters
// Compute at the centre of the element and write to: twiss.out
twiss,save,centre,file=twiss.out;

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stop;
```

sps.madx

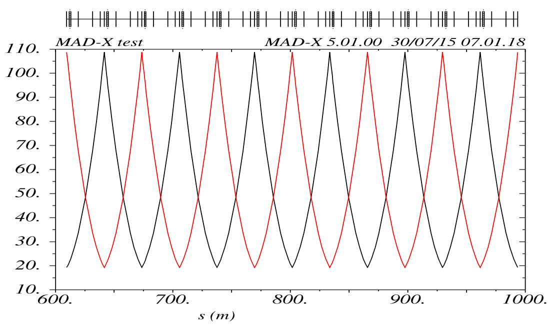
Typical MAD output (summary):

```
++++++ table: summ
          length             orbit5               alfa            gammatr
            6912                 -0     0.001667526597         24.4885807

              q1                dq1            betxmax              dxmax
     26.57999204   -8.828683153e-09        108.7763569        2.575386926

           dxrms             xcomax             xcorms                 q2
     1.926988371                  0                  0        26.62004577

             dq2            betymax              dymax              dyrms
  4.9186549e-08        108.7331749                  0                  0

          ycomax             ycorms             deltap            synch_1
               0                  0                  0                  0
```

Typical MAD output (all elements):

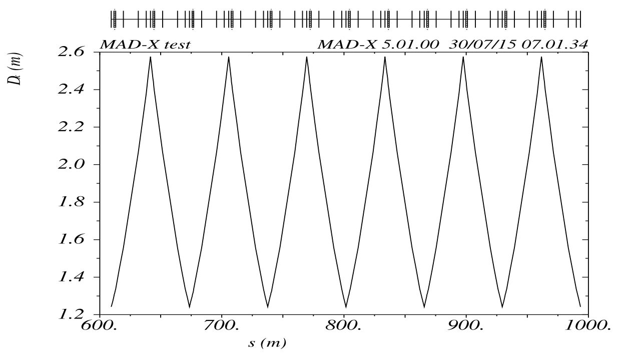
```
* NAME                              S          BETX          BETY
$ %s                              %le           %le           %le
 "CASSPS$START"                     0   101.5961579   20.70328425
 "START_MACHINE"                    0   101.5961579   20.70328425
 "DRIFT_0"                    0.77125   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
  .......
  .......
```

Graphical output (β)



Plotted only for: range=qd[10]/qd[16]

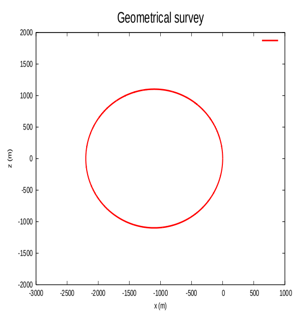
Graphical output (dispersion)

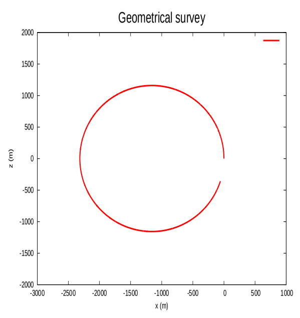


Plotted only for: range=qd[10]/qd[16]

Graphical output (geometrical survey)

- Output gives x, y, z, θ in absolute (terrestrial) coordinates, plotting x versus z should be a ring:





Optical matching

- To get the optical configuration you want
  $\rightarrow$ compute settings yourself or use MAD for matching
- Main applications:
  - Setting global optical parameters
    (e.g. tune, chromaticity) $\rightarrow$ part 1 (following)
  - Setting local optical parameters
    (e.g. β-function, dispersion ..) $\rightarrow$ part 2
  - Correction of imperfections $\rightarrow$ part 2

Matching global parameters

- Adjust strengths etc. to get desired properties (e.g. tune, chromaticity)
- Define the properties you want and the elements to vary
- Examples for <u>global</u> parameters (MAD convention):
  - Q1, Q2:(horizontal and vertical tune)
  - dQ1, dQ2:(horizontal and vertical chromaticity)

Matching global parameters - tune

!Example, match horizontal (Q1) and vertical (Q2) tunes:
!Vary the quadrupole strengths kqf and kqd
!Quadrupoles must be defined with: ..., k1:=kqf, ... etc.

```
match, sequence=cassps;
   global,sequence=cassps,Q1=26.58;     →   you want that !
   global,sequence=cassps,Q2=26.62;     →   you want that !
   vary,name=kqf, step=0.00001;     →   you vary that !
   vary,name=kqd, step=0.00001;     →   you vary that !
   Lmdif, calls=10, tolerance=1.0e-21;  → Method to use ! (just copy that ...)
endmatch;
```

Matching global parameters - chromaticity

!Example, match horizontal (dQ1) and vertical (dQ2) tunes:
!Vary the sextupole strengths ksf and ksd
!Sextupoles must be defined with: ..., k2:=ksf, ... etc.

```
match, sequence=cassps;
   global,sequence=cassps,DQ1=2.0;     →   you want that !
   global,sequence=cassps,DQ2=-1.5;     →   you want that !
   vary,name=ksf, step=0.00001;     →   you vary that !
   vary,name=ksd, step=0.00001;     →   you vary that !
   Lmdif, calls=10, tolerance=1.0e-21;  → Method to use ! (just copy that ...)
endmatch;
```

Changing MADX variables

- Deferred (:=) variables can be changed at any time during execution

```
use, period=cascell3;
ksf = 0.0;
ksd = 0.0;
select,flag=twiss,column=name,s,betx,muy,bety,dx,dy;
twiss,file=twiss1.out;

ksf = +0.017041/20.0;
ksd = −0.024714/20.0;
twiss,file=twiss2.out;
```

- Useful for: closed orbit, matching, chromaticity ...etc.

(Some comments ...)

- Input language seems heavy, but:
  - Can be interfaced to data base
  - Can be interfaced to other programs (e.g. Mathematica, Python,...)
  - Programs exist to generate the input interactively
  - Allows web based applications
  - Allows to develop complex tools

Linacs and beam lines !

They are not closed machines ! They have no periodic solution !

→ There are no β-functions etc. !

Must give INITIAL optical parameters !

```
twiss, betx=..., bety=..., alfx=..., ;

plot, haxis=s, vaxis=betx, bety, colour=100;
```

WARNING: careful with alfx, alfy when you have thin lenses !

MADX

- END OF PART 1 -

- YOUR TURN -

MADX - part 2

- We can:
  - Design and compute a regular lattice
  - Adjust machine parameters (tune, chromaticity, $\hat{\beta}$ ..)
- Solutions of exercises 1 - 3 at:

  http://cern.ch/Werner.Herr/CAS2015/solutions
- What next:
  - Machines with imperfections and corrections
  - Design of a dispersion suppressor
  - Design of a low β insertion

Error assignment

- MAD can assign errors to elements:
  - Alignment errors on all or selected elements
  - Field errors (up to high orders of multipole fields) on all or selected elements
- Errors are included in calculations (e.g. Twiss)
- Correction algorithms can be applied

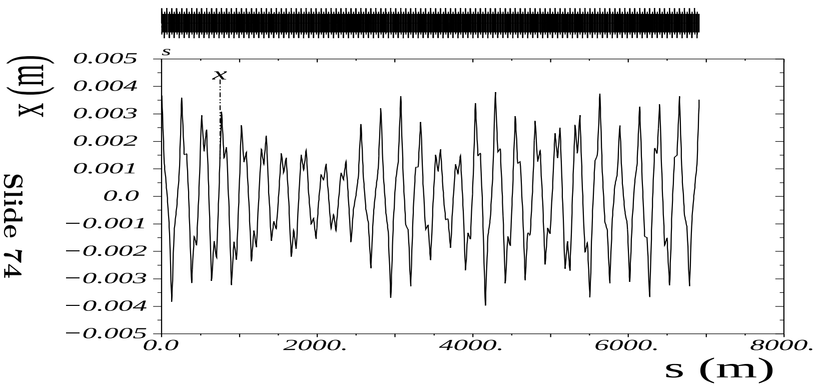
Error assignment

- Can define alignment errors (EALIGN):

```
! assign error to all elements starting with Q
select,flag=error,pattern="Q.*";
Ealign, dx:=tgauss(3.0)*1.0e-4, dy:=tgauss(3.0)*2.0e-4;
Twiss,file=orbit.out;   ! compute distorted machine
plot,haxis=s,vaxis=x,y;   ! plot orbits in x and y
```

- Can define field errors of any order (EFCOMP)
- Remember the := !
- See MADX Primer: page 14

Orbit with alignment errors



- Now we want to correct the orbit

How to measure an orbit ?

Needs Beam Position Monitors (keyword → MONITOR):

Gives position in one or both dimensions [$in \quad m$]

```
BPMV: VMONITOR, L=0.1;

BPMV01: VMONITOR, L=0.1;
BPMV02: VMONITOR, L=0.1;
BPMV03: BPMV;
BPMH02: HMONITOR, L=0.1;
BPMHV01: MONITOR, L=0.1;
```

For orbit correction: consider orbit only at monitors ...

How to correct an orbit ?

Needs Orbit corrector magnets (keyword → HKICKER/VKICKER):

The strength of a corrector is an angle (kick) [$in \quad rad$]

```
MCV: VKICKER, L=0.1;

MCV01: VKICKER, L=0.1, KICK := KCV01;
MCV02: VKICKER, L=0.1, KICK := KCV02;
MCV03: MCV, KICK := KCV03;
MCH02: HKICKER, L=0.1, KICK := KCH01;
```

Q: why do I use := ?

Orbit correction algorithms in MADX

- Best kick method (MICADO) in horizontal plane:
  ! Selected with MODE=MICADO

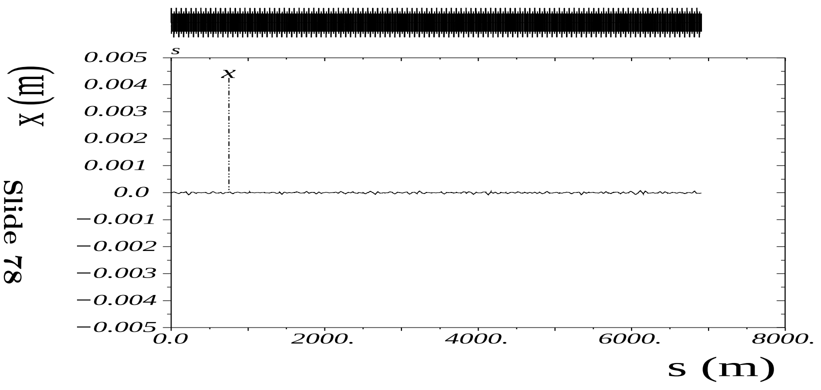
```
Correct,mode=MICADO,plane=x,
        clist="c.tab",mlist="m.tab";
```

- Singular Value Decomposition (SVD):
  ! Selected with MODE=SVD

```
Correct,mode=SVD,plane=x,
        clist="c.tab",mlist="m.tab";
```

- For details: see MADX Primer

Orbit after correction



Optical matching

- To get the optical configuration you want → matching
- Main applications:
  - → Setting global optical parameters (e.g. tune, chromaticity)
  - → Setting local optical parameters (e.g. β-function, dispersion ..)
  - → Correction of imperfections

Matching local parameters

- Get local optical properties, but leave the rest of the machine unchanged
- Adjust strength of individual machine elements
- Examples for local matching:
  - Low (or high) β insertions
  - Dispersion suppressors

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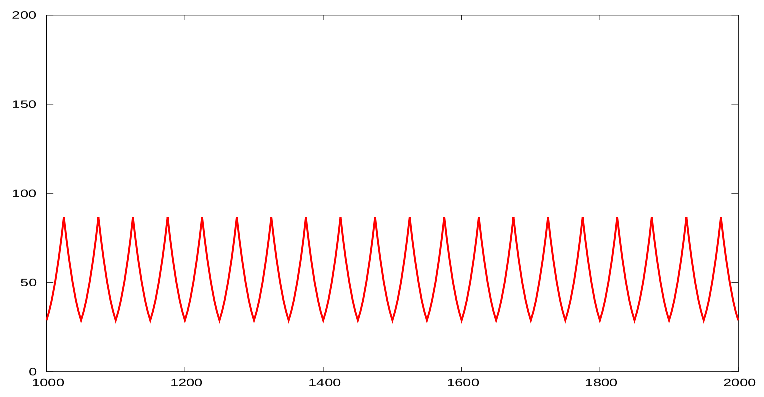
Local optical matching



- What we have ...

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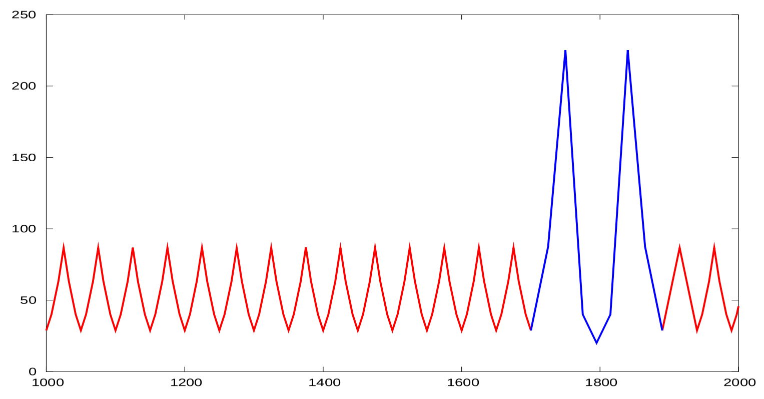
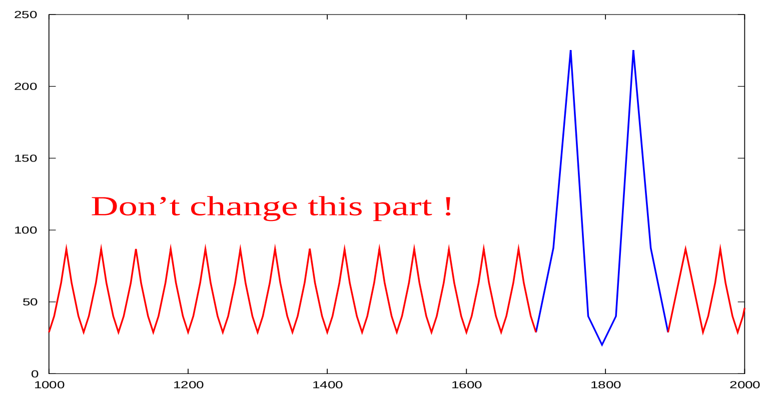
Local optical matching



- What we want ...

Local optical matching



- What we want ...

Insertions (I)

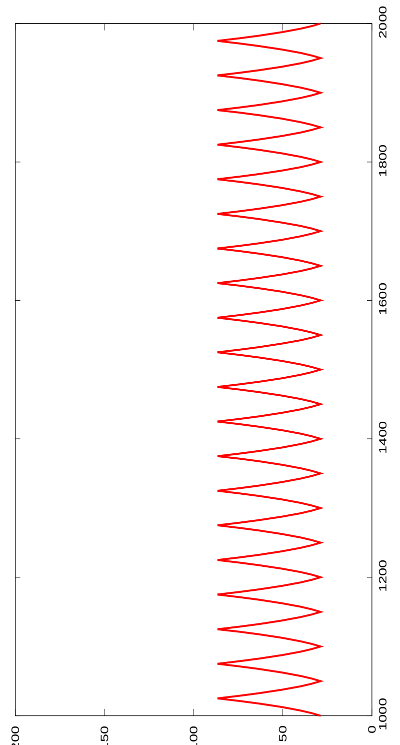
- How to add an insertion, e.g. two special cells ?

→ Start with periodic machine :

```
cassps: sequence, refer=centre, l=circum;
start_machine: marker, at = 0;
   n = 1;
   while (n <= ncell) {
      qfsps: qfsps,    at=(n-1)*lcell;
      mbsps: mbsps,    at=(n-1)*lcell + lcell*0.25;
      qdsps: qdsps,    at=(n-1)*lcell + lcell*0.50;
      mbsps: mbsps,    at=(n-1)*lcell + lcell*0.75;
   n = n + 1; }
end_machine: marker at=circum;
endsequence;
```

→ Split it into several pieces

Local optical matching



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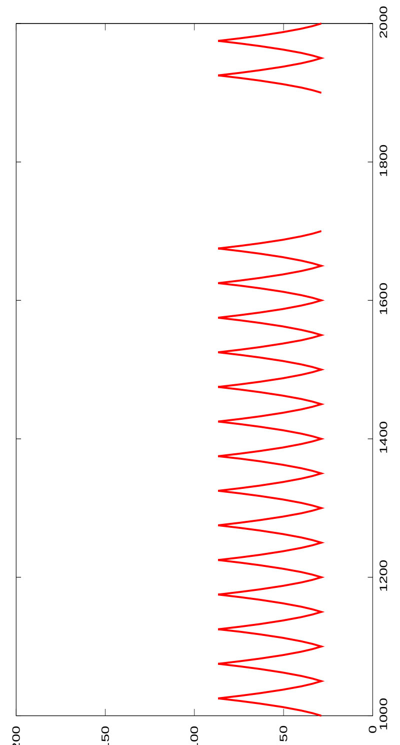
Local optical matching



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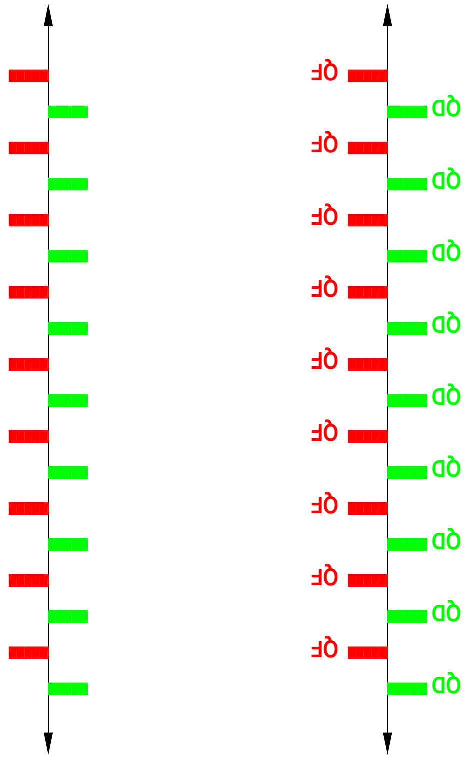
Original lattice



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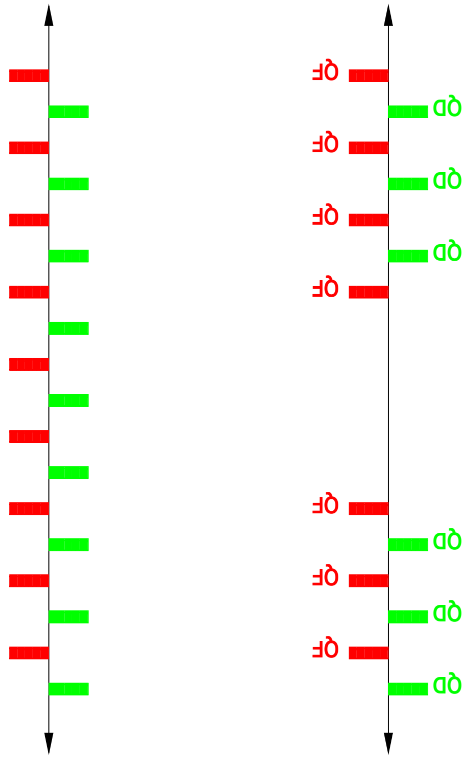
Space for insertion



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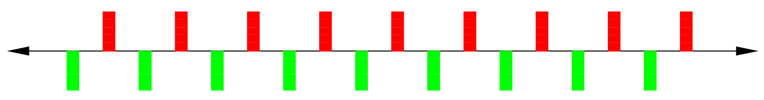
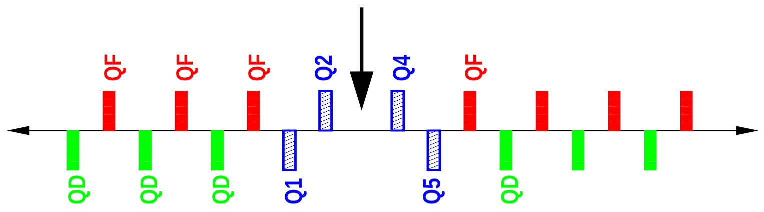
Adding quadrupoles



make a symmetric drift space: **Q2 – Q4**



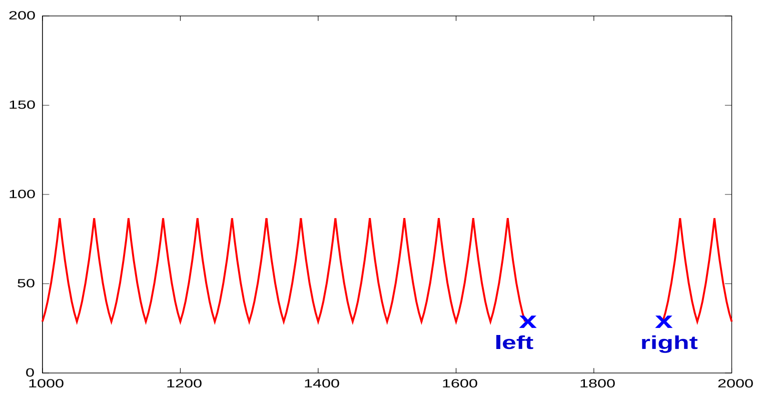
Insertions (II)

➡ Split it into several pieces

```
cassps: sequence, refer=centre, l=circum;
   n = 1;

while (n ≤ ncell-2) {

   qfsps: qfsps,   at=(n-1)*lcell;
   mbsps: mbsps,   at=(n-1)*lcell + lcell*0.25;
   qdsps: qdsps,   at=(n-1)*lcell + lcell*0.50;
   mbsps: mbsps,   at=(n-1)*lcell + lcell*0.75;
   n = n + 1;

}

   qf1  : qf1  ,   at=(ncell-2)*lcell;
   mbsps: mbsps,   at=(ncell-2)*lcell + lcell*0.25;
   qd1  : qd1  ,   at=(ncell-2)*lcell + lcell*0.50;
   mbsps: mbsps,   at=(ncell-2)*lcell + lcell*0.75;

   qf2  : qf2  ,   at=(ncell-1)*lcell;
   mbsps: mbsps,   at=(ncell-1)*lcell + lcell*0.25;
   qd2  : qd2  ,   at=(ncell-1)*lcell + lcell*0.50;
   mbsps: mbsps,   at=(ncell-1)*lcell + lcell*0.75;
endsequence;
```

s1_ins.seq

Local optical matching



- Fix parameters at beginning and end of insertion

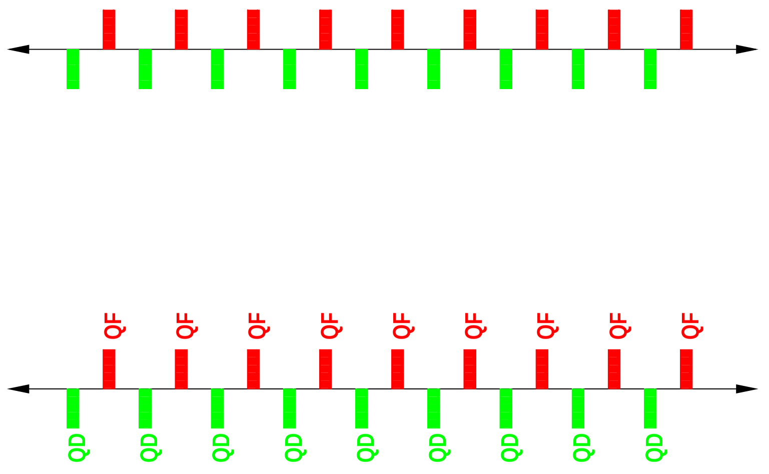
Matching techniques I(a)

- Use of markers:
  - → Have no effect on the optics
  - → Used to mark a position in the machine
  - → Can be used as reference in matching etc.
- Use:
  left: MARKER, at=$position$;
  right: MARKER, at=$position$;

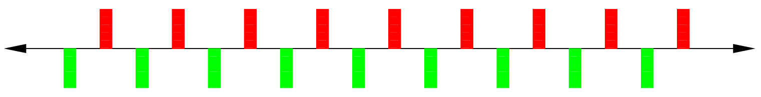
Matching techniques I(b)

- Markers:
  - can be used with RANGE in PLOT commands:
    → PLOT, range=$left/right$ ...;
  - can be used with RANGE in MATCH commands:
    → MATCH, range=$left/right$ ...;
  - can be used with PLACE in SAVEBETA commands to store twiss functions at position of the marker
    → SAVEBETA, label=$left\_beta$,place=$left$;

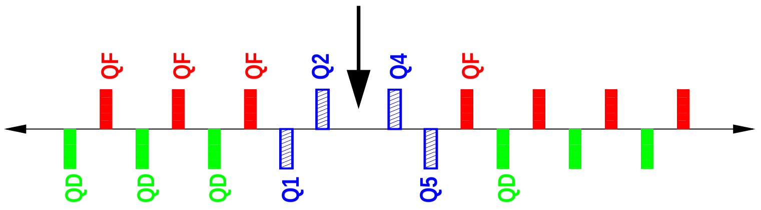
Use of MARKERS



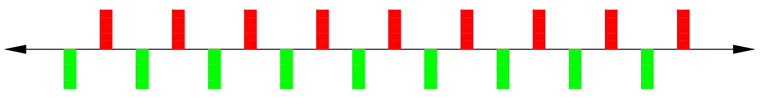
Use of MARKERS

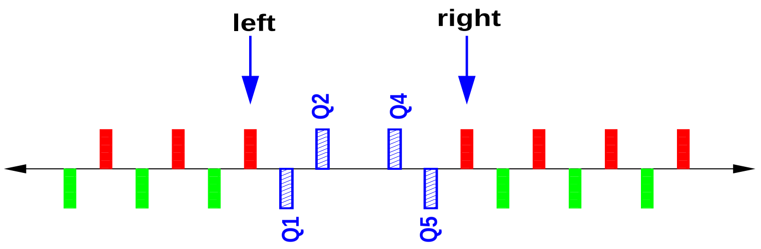


make a symmetric drift space: Q2 – Q4

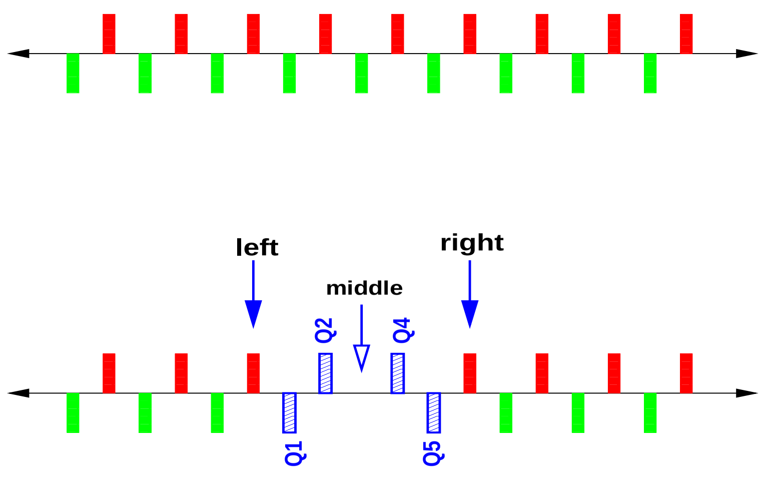


Use of MARKERS





Use of MARKERS



Matching techniques II

- Matching is done only locally (between markers left and right), not for the whole machine, needs initial and end conditions ($\beta_x, \alpha_x, ...$

```
match, range=left/right,betx=..., alfx=..., bety=...;
vary,name=kq1.l, step=0.00001;
vary,name=kq2.l, step=0.00001;
!  removed to become center of insertion
// vary,name=kq3.l, step=0.00001;
vary,name=kq4.l, step=0.00001;
vary,name=kq5.l, step=0.00001;
constraint,range=middle,sequence=cascell,betx=20.0,bety=50.0;
constraint,range=right,betx=..., alfx=..., bety=..., ...;
Lmdif, calls=100, tolerance=1.0e-21;
endmatch;
```

Clever: Using SAVEBETA to store optical functions

```
savebeta,label=tw_left,place=left;
savebeta,label=tw_right,place=right;
twiss;
kq3.l = 0.0; !  set to 0.0 after initial computation
match, sequence=cascell,range=left/right,beta0=tw_left;
vary,name=kq1.l, step=0.00001;
vary,name=kq2.l, step=0.00001;
// vary,name=kq3.l, step=0.00001;
vary,name=kq4.l, step=0.00001;
vary,name=kq5.l, step=0.00001;
constraint,range=middle,sequence=cascell,betx=20.0,bety=50.0;
constraint,range=right,sequence=cascell,beta0=tw_right;
Lmdif, calls=100, tolerance=1.0e-21;
endmatch;
```

Matching techniques IV

- Constraints on all quadrupoles, using limits:

```
match, sequence=cascell;
vary,name=kqf, step=0.00001;
vary,name=kqd, step=0.00001;
constraint,pattern="^qf.*",sequence=cascell,betx < 100.0;
constraint,pattern="^qd.*",sequence=cascell,bety < 100.0;
Lmdif, calls=100, tolerance=1.0e-21;
endmatch;
```

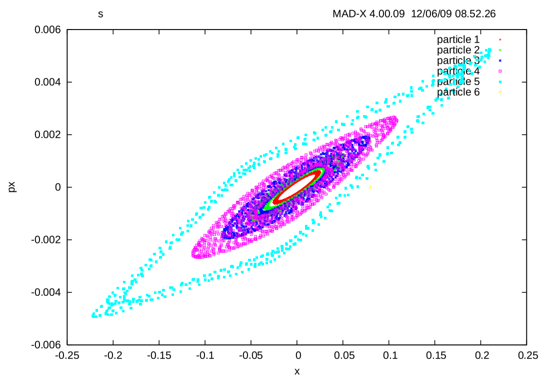
Particle tracking

- To track 4 particles for 1024 turns, add:

```
track,file=track.out,dump;
start, x= 2e-2, px=0, y= 2e-2, py=0;
start, x= 4e-2, px=0, y= 4e-2, py=0;
start, x= 6e-2, px=0, y= 6e-2, py=0;
start, x= 8e-2, px=0, y= 8e-2, py=0;
run,turns=1024;
endtrack;
plot, file="MAD_track",table=track,haxis=x,vaxis=px,
      particle=1,2,3,4, colour=1000, multiple, symbol=3;
plot, file="MAD_track",table=track,haxis=y,vaxis=py,
      particle=1,2,3,4, colour=1000, multiple, symbol=3;
```

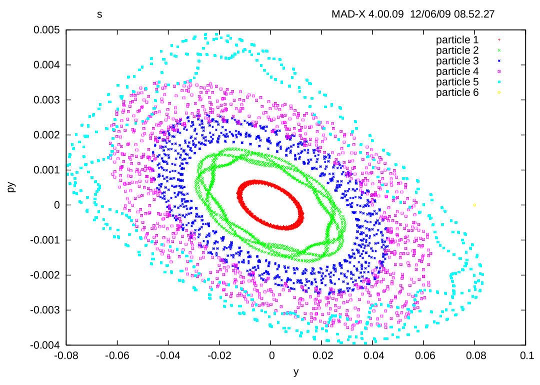
Particle tracking

- Phase space plot in horizontal coordinates:



Particle tracking

- Phase space plot in vertical coordinates:



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What we do not need (here !) ...

- Higher order effects
- IBS, beam-beam elements
- Equilibrium emittance (leptons)
- RF and acceleration

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