Science & Technology Facilities Council ASTeC

John Adams Institute for Accelerator Science

Lecture 7
Lattice design with MAD-X

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Lecture 8 – MADX introduction and examples

- This lecture is based on one by Ted Wilson (CERN) which was in turn based on a lecture by V. Ziemann (Uppsala University)
  - Installing/running MADX (on windows)
  - Input of elements and beamlines
  - Beta functions, tunes, dispersion
  - Matching
  - Examples

All credit to V. Ziemann for example input files
More examples are on the MAD-X website!

What is MAD-X?

"A program for accelerator design and simulation with a long history"
Developed from previous versions (MAD, MAD-8, then finally MAD-X in 2002).
User guide: http://mad.web.cern.ch/mad/uguide.html

- Uses a sequence of elements placed sequentially along a *reference orbit*
- *Reference orbit* is path of a charged particle having the central design momentum of the accelerator through idealised magnets (no fringe fields)
- The reference orbit consists of a series of straight line segments and circular arcs
- local curvilinear right handed coordinate system *(x,y,s)*

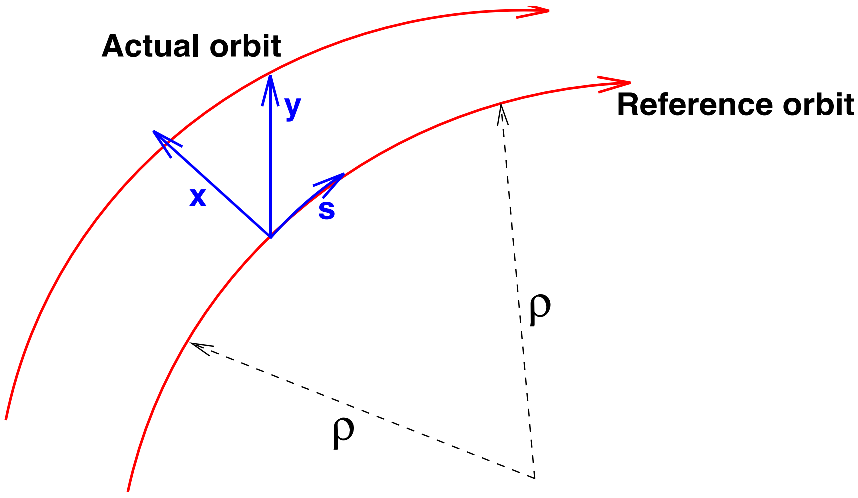


Figure 1: *Local coordinate system as used by MAD-X.*

What can it do?

- You can input magnets (& electrostatic elements) according to the manual
    - User guide: http://madx.web.cern.ch/madx/
- Calculate beta functions, tune, dispersion, chromaticity, momentum compaction numerically.
- Generates tables and plots (.ps)
- (tip: you might need to install ghostscript to view plots)

Why choose MAD-X?

- There are any number of tracking and beam optics codes, but MAD-X is *widely used* (especially at CERN), *well maintained* and *well documented*.
  - The more lattice design you do – the more you will appreciate this about MAD-X!
- What it can't do:
  - Acceleration and tracking simultaneously
  - Not so accurate at large excursions from closed orbit (as in an FFAG)
  - Complicated magnet geometries
  - Field maps

Installing MADX

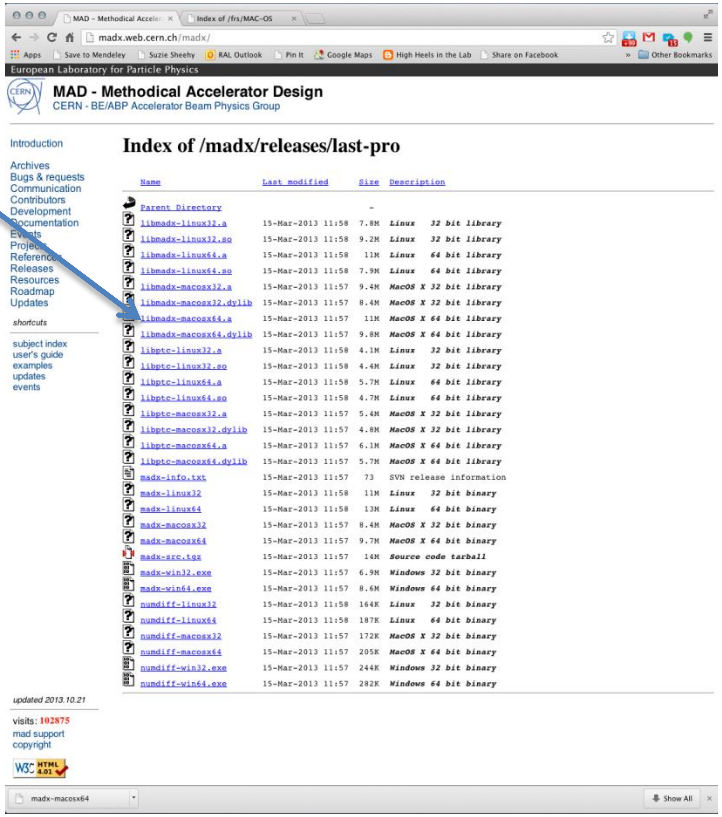
Go to ‘Updates’

Production version 5.02.00

Choose your system & download:

NOTE: You may need to make it executable

```
-rw-r--r--@ 1 Suzie  staff   9.7M  4 Nov 11:41 madx-macosx64
suzie-imac:2013Test Suzie$ chmod 777 madx-macosx64
suzie-imac:2013Test Suzie$ ls -lh
total 19968
-rwxrwxrwx@ 1 Suzie  staff   9.7M  4 Nov 11:41 madx-macosx64
suzie-imac:2013Test Suzie$
```


European Laboratory for Particle Physics

MAD - Methodical Accelerator Design

CERN - BE/ABP Accelerator Beam Physics Group

Index of /madx/releases/last-pro

Name	Last modified	Size	Description
Parent Directory		-	
libmadx-linux32.a	15-Mar-2013 11:58	7.8M	Linux 32 bit library
libmadx-linux32.so	15-Mar-2013 11:58	9.2M	Linux 32 bit library
libmadx-linux64.a	15-Mar-2013 11:58	11M	Linux 64 bit library
libmadx-linux64.so	15-Mar-2013 11:58	7.9M	Linux 64 bit library
libmadx-macosx32.a	15-Mar-2013 11:57	9.4M	MacOS X 32 bit library
libmadx-macosx32.dylib	15-Mar-2013 11:57	8.4M	MacOS X 32 bit library
libmadx-macosx64.a	15-Mar-2013 11:57	11M	MacOS X 64 bit library
libmadx-macosx64.dylib	15-Mar-2013 11:57	9.8M	MacOS X 64 bit library
libptc-linux32.a	15-Mar-2013 11:58	4.1M	Linux 32 bit library
libptc-linux32.so	15-Mar-2013 11:58	4.4M	Linux 32 bit library
libptc-linux64.a	15-Mar-2013 11:58	5.7M	Linux 64 bit library
libptc-linux64.so	15-Mar-2013 11:58	4.7M	Linux 64 bit library
libptc-macosx32.a	15-Mar-2013 11:57	5.4M	MacOS X 32 bit library
libptc-macosx32.dylib	15-Mar-2013 11:57	4.8M	MacOS X 32 bit library
libptc-macosx64.a	15-Mar-2013 11:57	6.1M	MacOS X 64 bit library
libptc-macosx64.dylib	15-Mar-2013 11:57	5.7M	MacOS X 64 bit library
madx-info.txt	15-Mar-2013 11:57	73	SVN release information
madx-linux32	15-Mar-2013 11:58	11M	Linux 32 bit binary
madx-linux64	15-Mar-2013 11:58	13M	Linux 64 bit binary
madx-macosx32	15-Mar-2013 11:57	8.4M	MacOS X 32 bit binary
madx-macosx64	15-Mar-2013 11:57	9.7M	MacOS X 64 bit binary
madx-src.tgz	15-Mar-2013 11:57	14M	Source code tarball
madx-win32.exe	15-Mar-2013 11:57	6.9M	Windows 32 bit binary
madx-win64.exe	15-Mar-2013 11:57	8.6M	Windows 64 bit binary
numdiff-linux32	15-Mar-2013 11:58	164K	Linux 32 bit binary
numdiff-linux64	15-Mar-2013 11:58	187K	Linux 64 bit binary
numdiff-macosx32	15-Mar-2013 11:57	172K	MacOS X 32 bit binary
numdiff-macosx64	15-Mar-2013 11:57	205K	MacOS X 64 bit binary
numdiff-win32.exe	15-Mar-2013 11:57	244K	Windows 32 bit binary
numdiff-win64.exe	15-Mar-2013 11:57	282K	Windows 64 bit binary

How to run MADX

- In command prompt:
- Go to directory (with madx.exe and input files)
- `madx.exe < inputfile > outputfile`
- Or you can add the madx.exe location to your path (if you know how…)

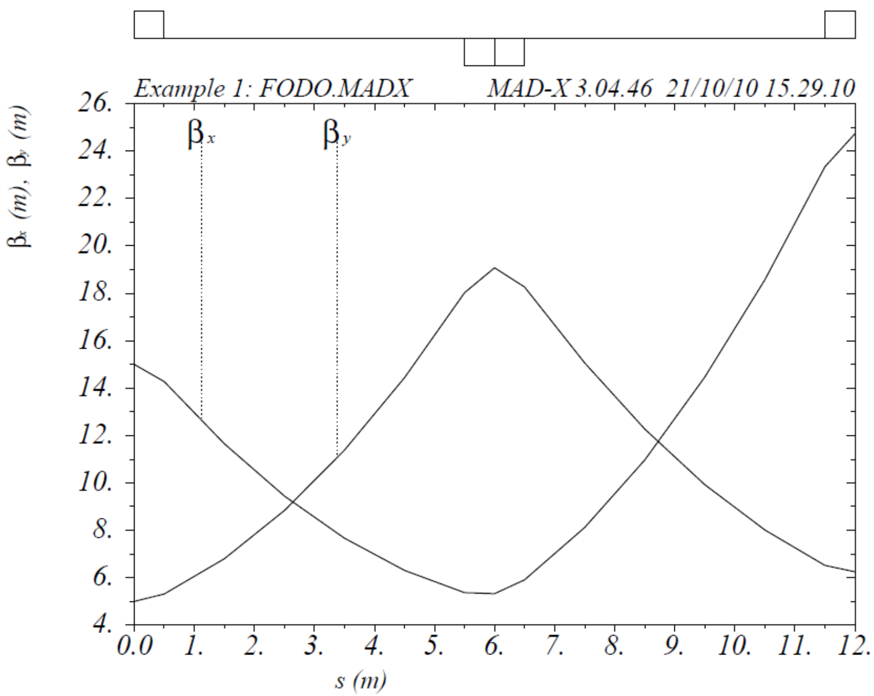
An input file – Basic FODO

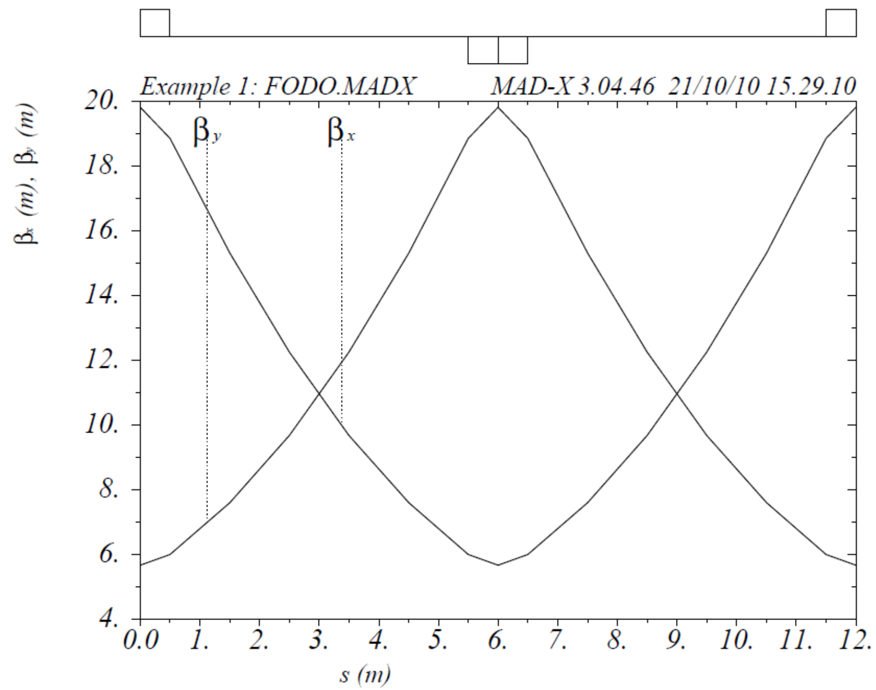
```
//
// MADX Example 1: FODO cell
// Author: V. Ziemann, Uppsala University
// Date: 060910
// UPDATED SUZIE SHEEHY 04/11/2013 FOR MADX VERSION 5.01.00

TITLE,'Example 1: FODO.MADX';

BEAM, PARTICLE=ELECTRON,PC=3.0;

D: DRIFT,L=1.0;
QF: QUADRUPOLE,L=0.5,K1=0.2;
QD: QUADRUPOLE,L=0.5,K1=-0.2;

FODO: LINE=(QF,5*(D),QD,QD,5*(D),QF);

SETPLOT, POST=2, FONT=-1;

USE, PERIOD=FODO;
TWISS,SAVE,BETX=15.0,BETY=5.0;
PLOT,HAXIS=S, VAXIS=BETX, BETY, NOVERSION=TRUE, TITLE='unmatched beta functions';

//Here MATCH is used as a single command this finds periodic solution
USE, PERIOD=FODO;
MATCH, SEQUENCE=FODO;
TWISS, SAVE;
PLOT,HAXIS=S, VAXIS=BETX, BETY, NOVERSION=TRUE, TITLE='matched beta functions';

Value, TABLE(SUMM,Q1);
Value, TABLE(SUMM,Q2);
WRITE,TABLE=SUMM,FILE=print.dat;
```

Annotations:

- // comments out a line
- TITLE at top of output
- Define particle type and momentum (pc) GeV/c. Or can use ENERGY in GeV.
- Elements are given in the manual including definitions of L, K1 etc…
- Define a 'line' –can be a cell or a whole beamline that you will USE.
- Calculate beta functions from starting values
- Plot beta values from TWISS (internal table)
- Match the periodic solution (+Plot that)
- Output to tables

Result of a MADX run





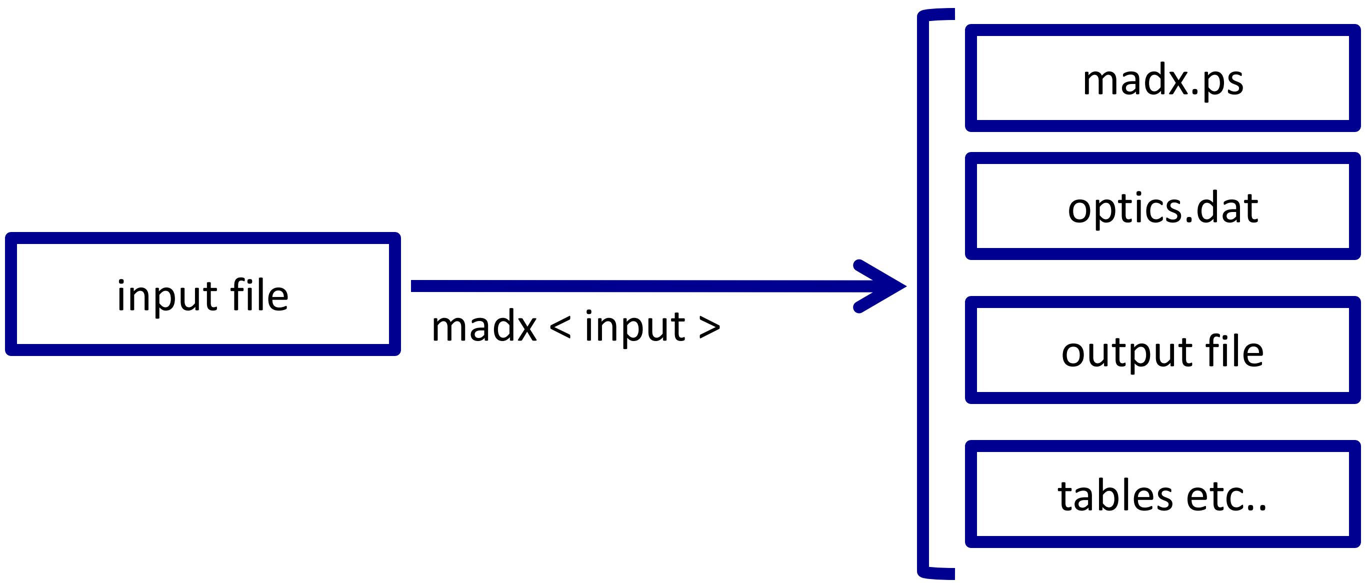
With βx starting at 15m (βy at 5m)

If the line is matched (periodic)

$\beta_{start} = \beta_{end}$

Output files

- Optics.dat
- Your specified output file madx< input > <u>output</u>
- Can specify tables

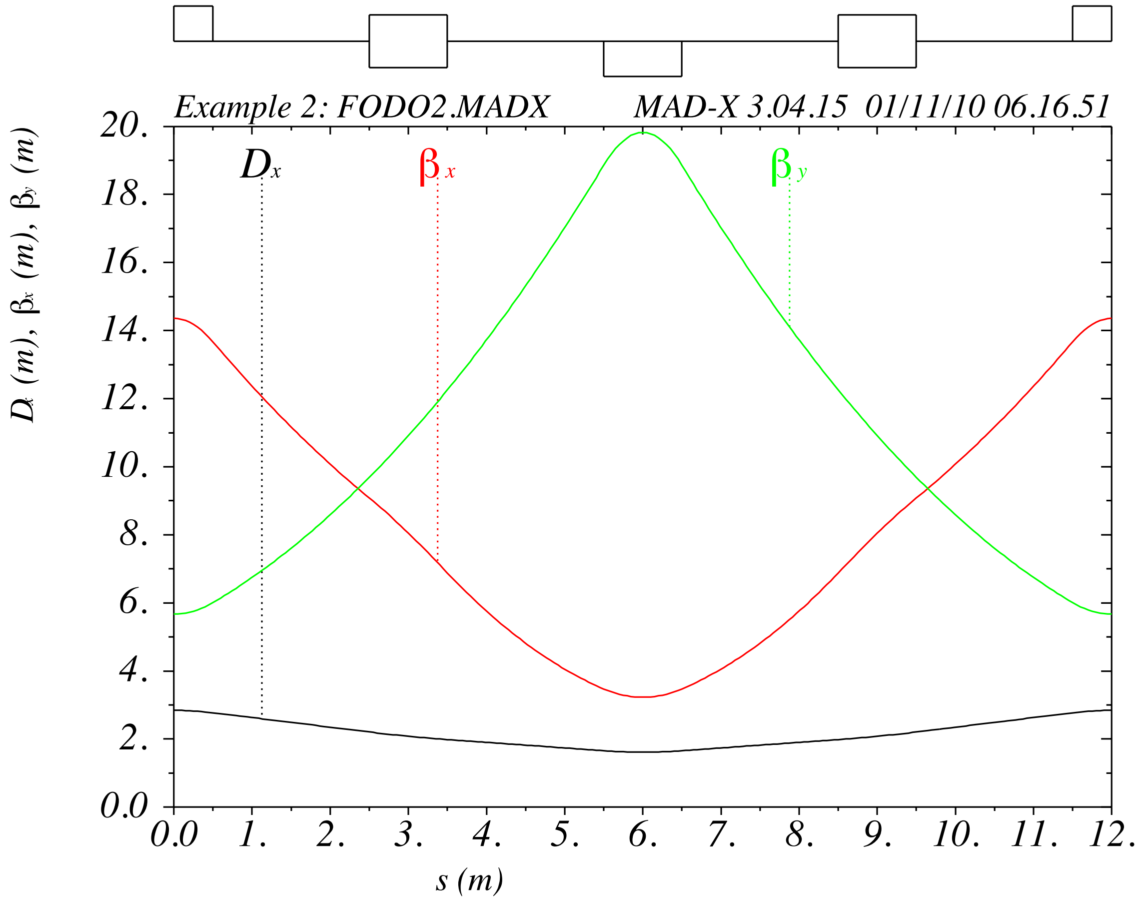


Add bending magnets

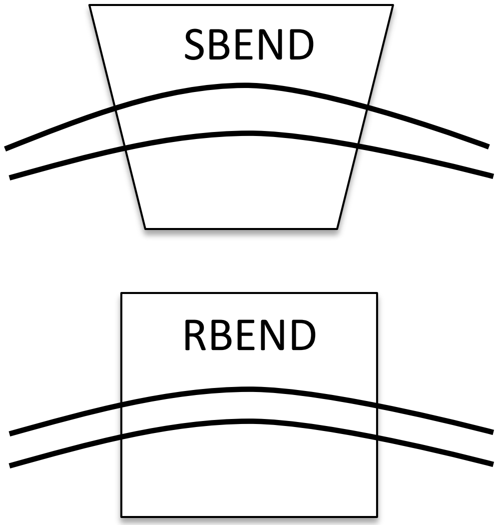
- Can introduce your own parameters (watch the :=)
- Can use alternative 'sequence' format
- Let's add dipoles
- Look at dispersion

```
TITLE,'Example 2: FODO2.MADX';
BEAM, PARTICLE=ELECTRON,PC=3.0;
DEGREE:=PI/180.0;               // for readability

QF: QUADRUPOLE,L=0.5,K1=0.2;      // still half-length
QD: QUADRUPOLE,L=1.0,K1=-0.2;     // changed to full length
B: SBEND,L=1.0,ANGLE=15.0*DEGREE;  // added dipole

FODO: SEQUENCE,REFER=ENTRY,L=12.0;
  QF1:   QF,     AT=0.0;
  B1:    B,      AT=2.5;
  QD1:   QD,     AT=5.5;
  B2:    B,      AT=8.5;
  QF2:   QF,     AT=11.5;
ENDSEQUENCE;

USE, PERIOD=FODO;
//MATCH, SEQUENCE=FODO;     //Uncomment to match
SELECT,FLAG=SECTORMAP,clear;
SELECT,FLAG=TWISS,column=name,s,betx,bety;
TWISS, file=optics.dat,sectormap;

PLOT,HAXIS=S, COLOUR=100, VAXIS=DX, BETX, BETY,
INTERPOLATE=TRUE;

Value, TABLE(SUMM,Q1);
Value, TABLE(SUMM,Q2);
```

Output from FODO with dipole

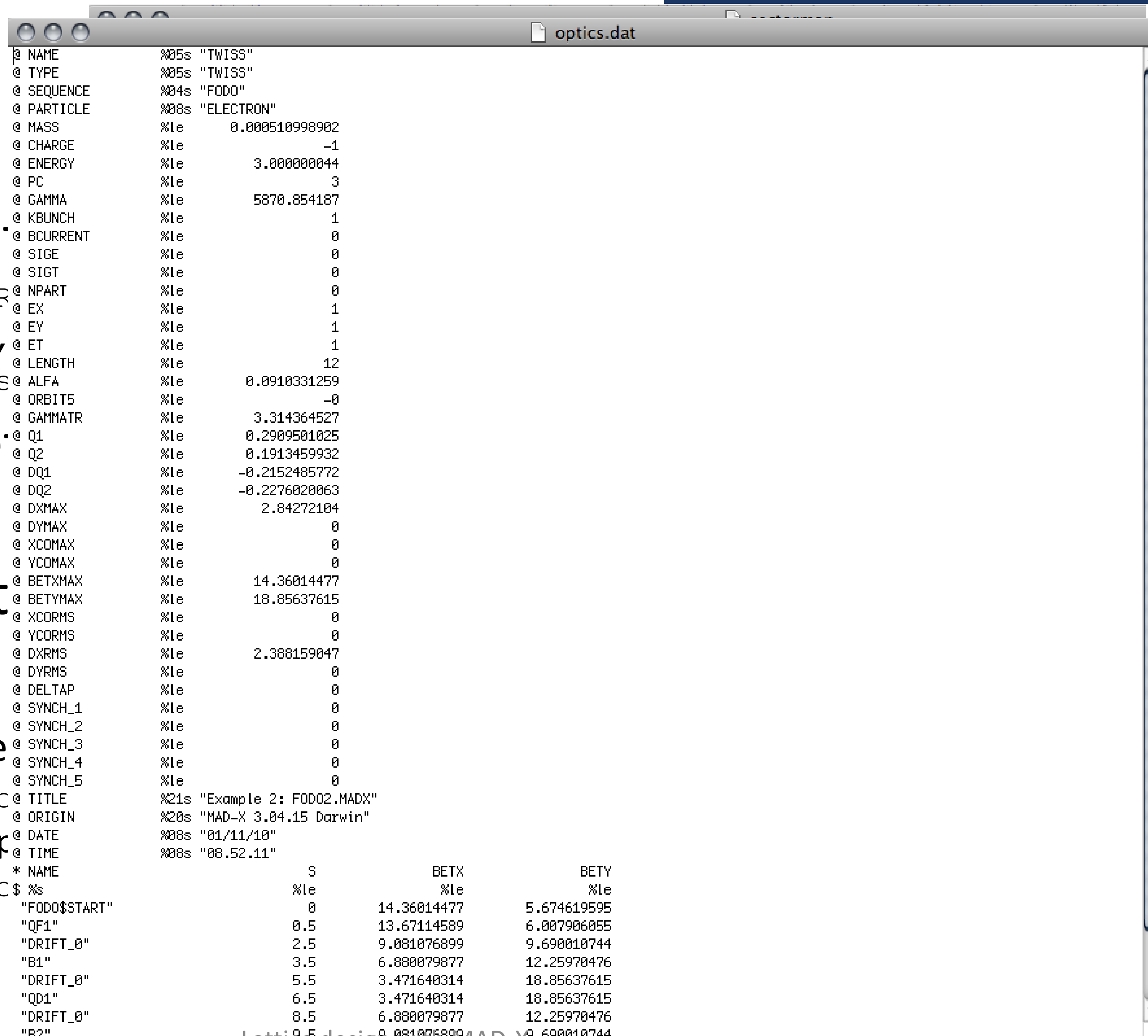


Note the colours!
We now have dispersion (from bending magnet)
Focusing changed as we used SBEND



- If you add ·
SELECT,FLAG=SECTOR
SELECT,FLAG=TWISS,
TWISS, file=optics
- You will ge matrices
- and an out

You can customise
select,flag=my_sec
Or even select by comp
select,flag=my_sec



```
@ NAME             %05s "TWISS"
@ TYPE             %05s "TWISS"
@ SEQUENCE         %04s "FODO"
@ PARTICLE         %08s "ELECTRON"
@ MASS             %le     0.000510998902
@ CHARGE           %le                 -1
@ ENERGY           %le        3.000000044
@ PC               %le                  3
@ GAMMA            %le        5870.854187
@ 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                 12
@ ALFA             %le       0.0910331259
@ ORBIT5           %le                 -0
@ GAMMATR          %le        3.314364527
@ Q1               %le       0.2909501025
@ Q2               %le       0.1913459932
@ DQ1              %le      -0.2152485772
@ DQ2              %le      -0.2276020063
@ DXMAX            %le         2.84272104
@ DYMAX            %le                  0
@ XCOMAX           %le                  0
@ YCOMAX           %le                  0
@ BETXMAX          %le        14.36014477
@ BETYMAX          %le        18.85637615
@ XCORMS           %le                  0
@ YCORMS           %le                  0
@ DXRMS            %le        2.388159047
@ DYRMS            %le                  0
@ DELTAP           %le                  0
@ SYNCH_1          %le                  0
@ SYNCH_2          %le                  0
@ SYNCH_3          %le                  0
@ SYNCH_4          %le                  0
@ SYNCH_5          %le                  0
@ TITLE            %21s "Example 2: FODO2.MADX"
@ ORIGIN           %20s "MAD-X 3.04.15 Darwin"
@ DATE             %08s "01/11/10"
@ TIME             %08s "08.52.11"
* NAME                               S              BETX              BETY
$ %s                               %le               %le               %le
 "FODO$START"                        0       14.36014477       5.674619595
 "QF1"                             0.5       13.67114589       6.007906055
 "DRIFT_0"                         2.5       9.081076899       9.690010744
 "B1"                              3.5       6.880079877       12.25970476
 "DRIFT_0"                         5.5       3.471640314       18.85637615
 "QD1"                             6.5       3.471640314       18.85637615
 "DRIFT_0"                         8.5       6.880079877       12.25970476
 "B2"                              9.5       9.081076899       9.690010744
```

Matching

- Matching lets MAD-X do the tedious work for you!
- Before MATCH select at least one sequence (USE)
- Initiated by the MATCH command
- Initiating:

```
MATCH, SEQUENCE='name1', 'name2',..,'nameX';
```

- Can define constraints & variables (magnets) to achieve aim

```
MATCH, SEQUENCE = FODO;
CONSTRAINT,SEQUENCE=FODO, RANGE=#E, MUX=0.1666666, MUY=0.25;
VARY, NAME=QF->K1, STEP=1E-6;
VARY, NAME=QD->K1, STEP=1E-6;
LMDIF,CALLS=500,TOLERANCE=1E-20;
ENDMATCH;
```

Matching input file

```
TITLE,'Example 3: MATCH1.MADX';
BEAM, PARTICLE=ELECTRON,PC=3.0;

D: DRIFT,L=1.0;
QF: QUADRUPOLE,L=0.5,K1:=0.2;
QD: QUADRUPOLE,L=0.5,K1:=-0.2;

FODO: LINE=(QF,5*(D),QD,QD,5*(D),QF);
USE, PERIOD=FODO;

//....match phase advance at end of cell to 60 and 90 degrees
MATCH, SEQUENCE=FODO;
CONSTRAINT,SEQUENCE=FODO,RANGE=#E,MUX=0.16666666,MUY=0.25;
VARY,NAME=QF->K1,STEP=1E-6;
VARY,NAME=QD->K1,STEP=1E-6;
LMDIF,CALLS=500,TOLERANCE=1E-20;
ENDMATCH;

SELECT,FLAG=SECTORMAP,clear;
SELECT,FLAG=TWISS,column=name,s,betx,alfx,bety,alfy;
TWISS, file=optics.dat,sectormap;

PLOT,HAXIS=S, VAXIS=BETX, BETY;
Value, TABLE(SUMM,Q1);  // verify result
Value, TABLE(SUMM,Q2);
```

Matching commands

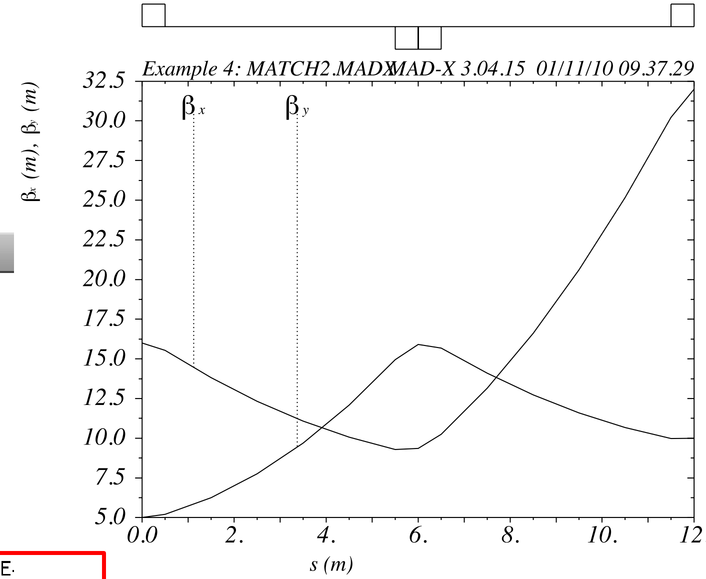
Print out final values of matching

Matching example

- Demonstration MATCH1.MADX

Fitting beta functions

- Use MATCH2.MADX



match2.out

```
Initial Penalty Function =   0.87329908E+02


call:       5   Penalty function =   0.14687632E+02
call:       8   Penalty function =   0.52122712E+00
call:      11   Penalty function =   0.14867643E-03
call:      14   Penalty function =   0.17048760E-10
call:      17   Penalty function =   0.86820304E-19
call:      20   Penalty function =   0.66895405E-27
 ++++++++++ LMDIF ended: converged successfully
call:      20   Penalty function =   0.66895405E-27
fodo$end:1                betx         4     3.20000000E+01     3.20000000E+01     5.04870979E
fodo$end:1                bety         4     1.00000000E+01     1.00000000E+01     6.18466950E-2
qf->k1                    1.21494427E-01    -1.00000000E+20     1.00000000E+20
qd->k1                   -1.58047975E-01    -1.00000000E+20     1.00000000E+20

 GXPLOT-X11  1.50 initialized

 plot number =  1

  +++++++++++++++++++++++++++++++++++++++++++
  +               MAD-X 3.04.15             +
  + Code Modification Date: 15.01.2008      +
  + Execution Time Stamp: 01.11.10 09.39.37 +
  +++++++++++++++++++++++++++++++++++++++++++
//

// MADX Example 1: FODO matching final beta function
```

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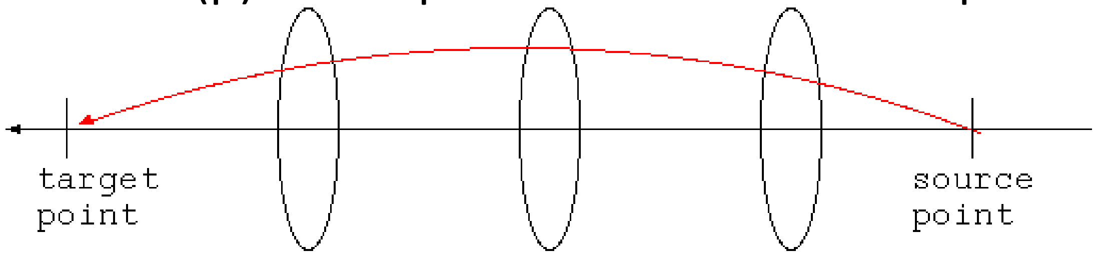
Transfer matrix matching

- Sometimes want to constrain transfer matrix elements to some value.
- For example R_{16}=0 and R_{26}=0 will make the horizontal position and angle independent of the momentum after a beamline.
- This is called an 'Achromat'.
- Other versions are imaginable
- point-to-point imaging→ R12 = 0.
  - This means sin(μ)=0 or a phase advance of a multiple of π.



Examples in MAD-X

- FODO arcs
- Dispersion suppressor
- ‘Telescopes’ for low-β
- Synchrotron radiation lattices + achromats

Is that it?

- 'the not-so-ideal world'
- What happens to α,β,γ if we stop focusing for a distance?

$$\beta(s) = \beta_0 - 2\alpha_0 s + \gamma_0 s^2$$

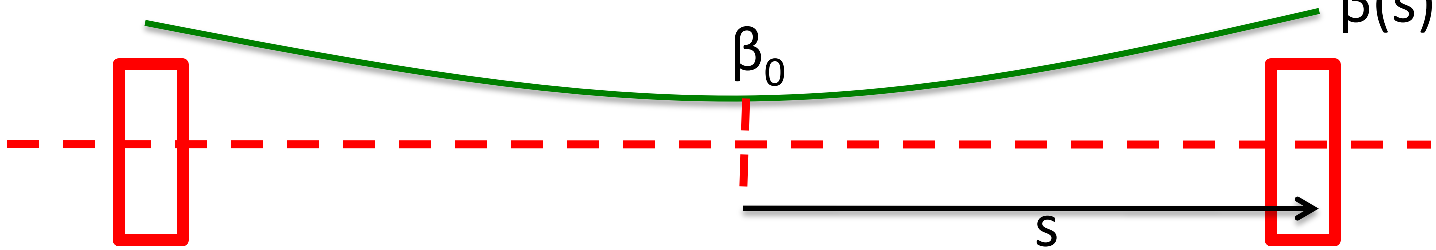
$$\alpha(s) = \alpha_0 - \gamma_0 s$$

$$\gamma(s) = \gamma_0$$

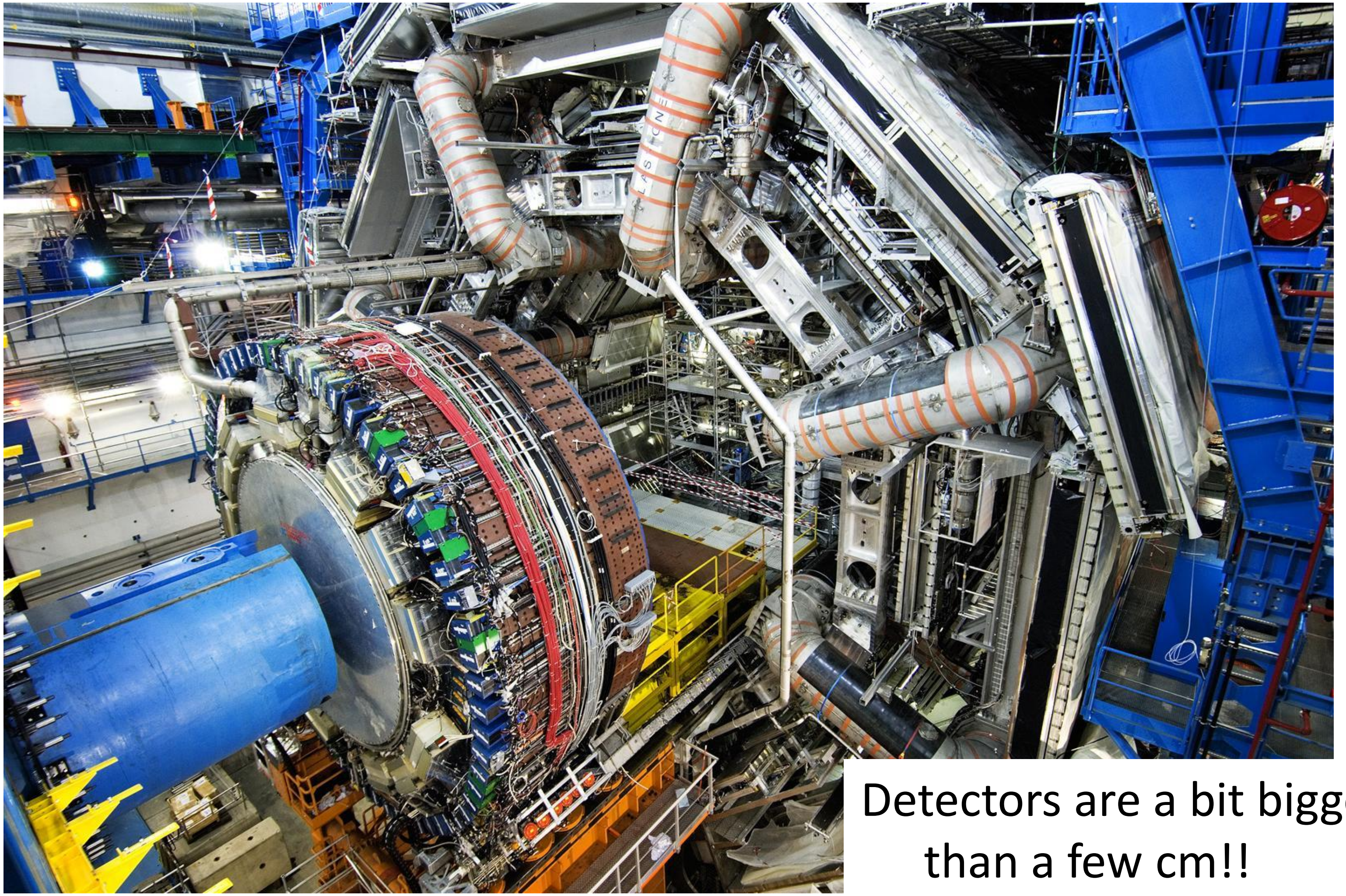
The drift length:

$$M = \begin{bmatrix} 1 & s \\ 0 & 1 \end{bmatrix}$$

- If we take the center of a drift (α_0=0), we find $\beta(s) = \beta_0 + \frac{s^2}{\beta_0}$
- It doesn't matter what you do – β will grow!



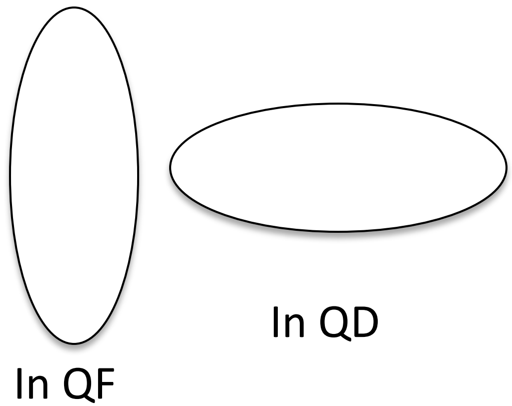
Seems fine, until…



Detectors are a bit bigger than a few cm!!

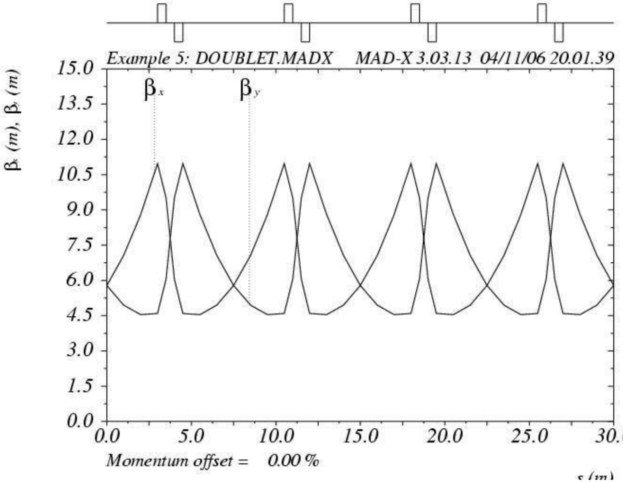
FODO Arcs

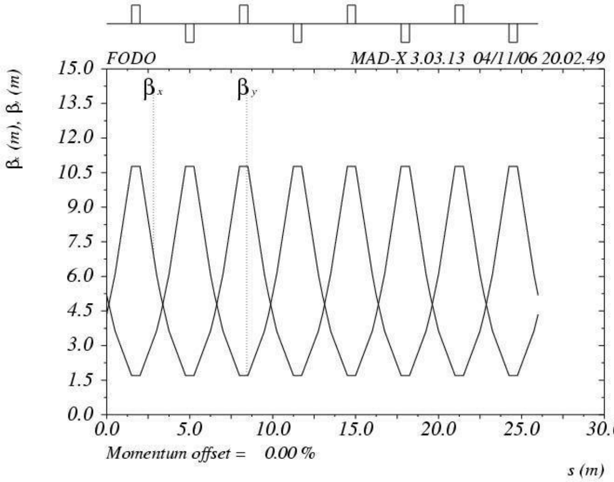
- Usually in colliders – take beam between interaction regions
- Simple and tunable (β_x large in QF, β_y at QD)
- Moderate quad strengths
- The beam is not round
- In arcs dipoles generate dispersion



FD Doublet Lattice

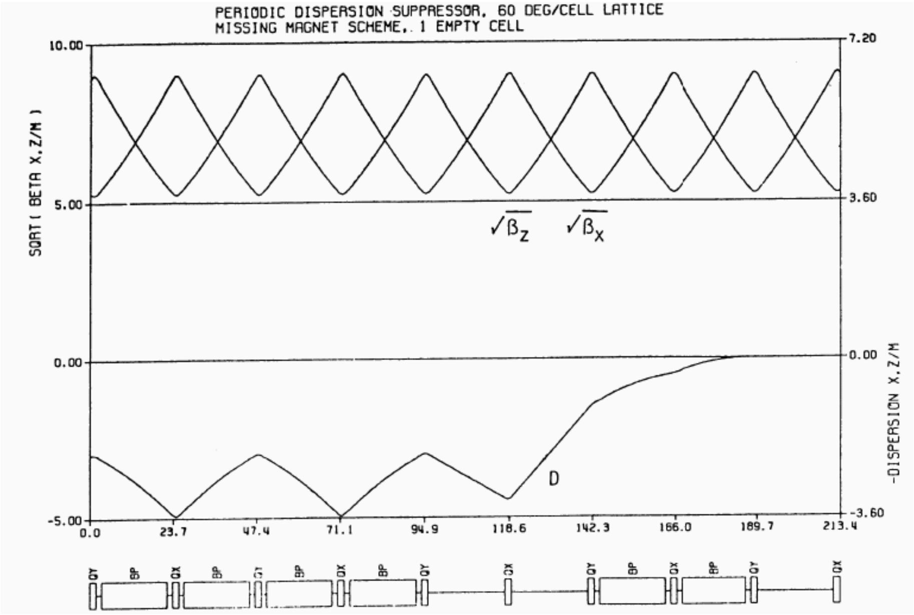
- More space between quads
- Stronger quad strengths
- Round beams
- Used in CTF3 linac



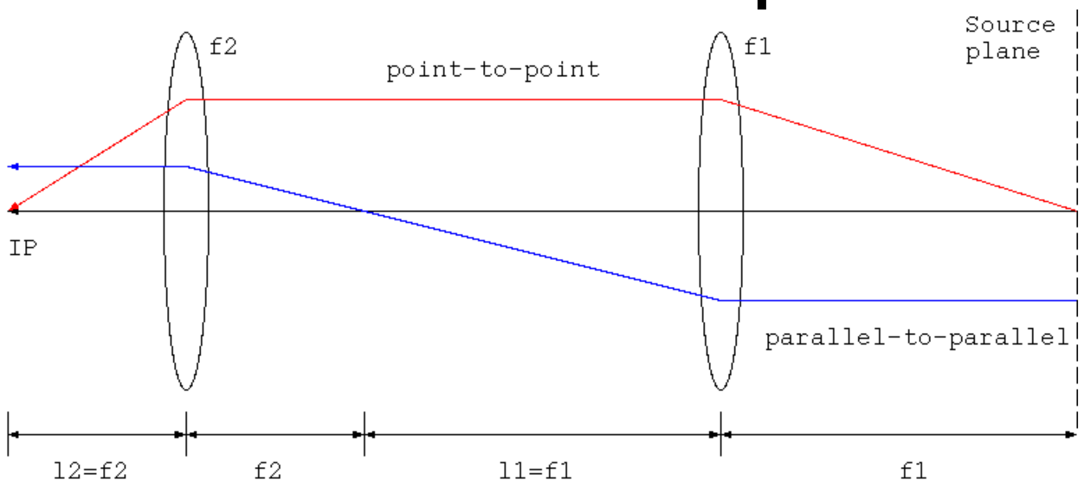


Dispersion suppressor

- Want small spot size at interaction point
- Spot size: $\sqrt{\varepsilon\beta + (D\Delta p/p)^2}$
- Missing magnet dispersion suppression scheme
- Works with proper phase advance between elements



Telescope and low β



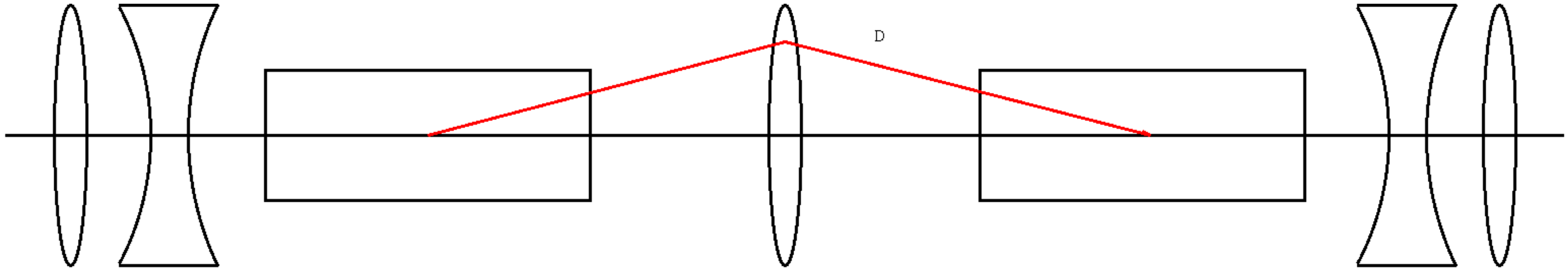
$$\begin{pmatrix} 1 & l_1 \\ 0 & 1 \end{pmatrix}\begin{pmatrix} 1 & 0 \\ -1/f_1 & 1 \end{pmatrix}\begin{pmatrix} 1 & l_1 \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} 1 - l_1/f_1 & 2l_1 - l_1^2/f_1 \\ -1/f_1 & 1 - l_1/f_1 \end{pmatrix}$$

For one module with $l_1 = f_1$
$$\begin{pmatrix} 0 & f_1 \\ -1/f_1 & 0 \end{pmatrix}$$

For both modules:
$$R = \begin{pmatrix} f_2/f_1 & 0 \\ 0 & -f_1/f_2 \end{pmatrix}$$

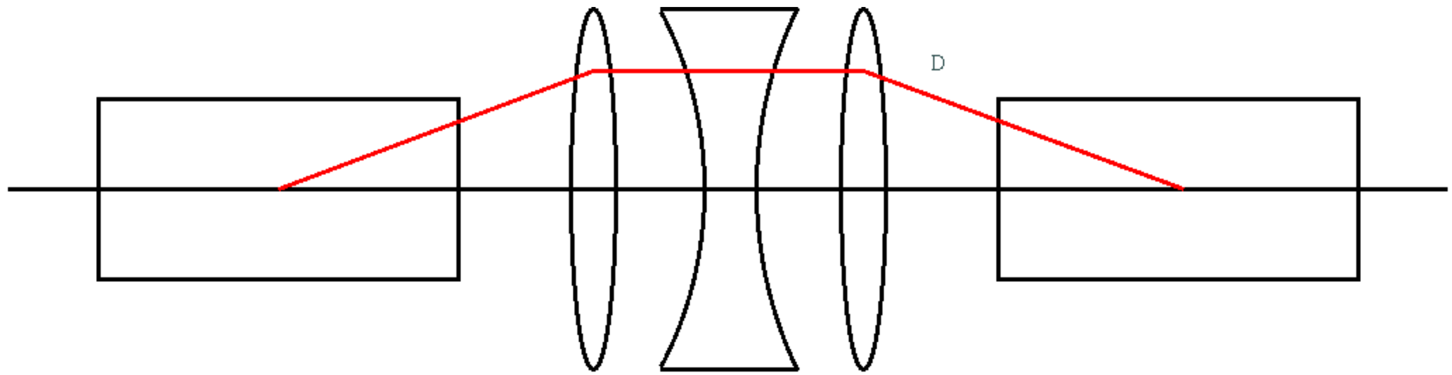
- Used in colliders to achieve small beam size at IP
- Doublet or Triplet
- Point-to-point $R_{12}=0$
- Parallel to parallel $R_{21}=0$
- R_{11}=demagnification
- Ratio of focal lengths
- Needs to work in both planes with doublets/triplets

Double bend achromat



- One dipole generates dispersion and the next, which is 180 degrees apart will take it out again
- Remember: the dispersion is the orbit of a particle with slightly too high momentum w.r.t the reference particle
- Quadrupoles are used to make βx in dipoles small

Triplet achromat



- Do the 180 degrees in the horizontal plane and the beta matching by quads between dipoles
- very compact, few magnets, but not flexible

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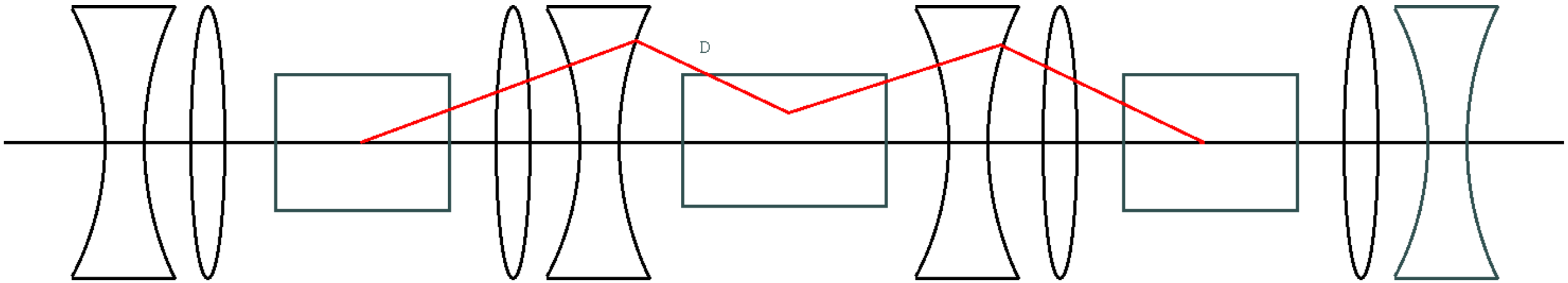
Triple bend achromat



- Small emittance.
- Very flexible due to large number of quadrupoles.
- Adjacent drift space can be made long to accommodate undulators/wigglers.

Resources

- Many examples available at the MAD-X website
  - A helpful 'primer' by W. Herr:
    http://madx.web.cern.ch/madx/doc/madx_primer.pdf

You can always ask me or another lecturer – though we can't promise to know the answer!