JINA

Tutorial:
Introduction to computer code for ion-optical calculations COSY Infinity

Learning COSY, Resources

- COSY-Infinity is a modern ion-optical code, arbitrary orders
- Written by Martin Berz, MSU, http://cosy.pa.msu.edu
- (Register and download code and manuals)
- Computing with COSY (Beam Physics Manual, BPM)
- COSY is a fully programmable (Programmer's Manual)
- Examples (Introduction to COSY INFINITY)

- The preceding Lecture 1 has introduced you to the ion-optical formalism. Detailed design, optimization and simulations are done with ion-optical codes.
- This tutorial is designed to introduce you to the powerful ion-optical code COSY Infinity and get you started with simple examples.

Example1.fox

- Calculate the transfer matrix (map) of a quadrupole doublet

```
INCLUDE 'COSY' ;
PROCEDURE RUN ;
 OV 3 2 0 ; {order 3, phase space dim 2, # of parameters 0}
 RP 10 4 2 ; {kin. energy, mass 4 amu, charge 2}
 UM ; {sets maps to unity}
 DL .1; {drift length .1 m}
 MQ .2 .1 .05; {quad, length .2 m, field 0.1 T, aperture .05 m}
 DL .1 ;{drift length .1 m}
 MQ .2 -.1 .05; {defoc. quad}
 Dl .1;{drift length .1 m}

 PM 6 ; {Prints Transfer Matrix on Screen}
 PM 11 ;{Prints Transfer Matrix to file fort.11}

ENDPROCEDURE ;
RUN ; END ;
```

COSY- Coordinates, Definitions (Beam Physics Manual (BPM))

3.2.1 The Coordinates

COSY INFINITY performs all its calculations in the following scaled coordinates:

$$
\begin{array}{rclrcl}
r_1 & = & x, & r_2 & = & a = p_x/p_0, \\
r_3 & = & y, & r_4 & = & b = p_y/p_0, \\
r_5 & = & l = -(t - t_0)v_0\gamma/(1+\gamma) & r_6 & = & \delta_K = (K - K_0)/K_0 \\
r_7 & = & \delta_m = (m - m_0)/m_0 & r_8 & = & \delta_z = (z - z_0)/z_0
\end{array}
$$

The first six variables form three canonically conjugate pairs in which the map is symplectic. The units of the positions x and y is meters. p_0, K_0, v_0, t_0 and γ are the momentum, kinetic energy, velocity, time of flight, and total energy over m_0c^2, respectively. m and z denote mass and charge of the reference particle, respectively.

3.2.2 Defining the Beam

All particle optical coordinates are relative to a reference particle which can be defined with the command

RP <kinetic energy in MeV> <mass in amu> <charge in units> ;

COSY- Supported Elements, Examples (BPM)

The simplest particle optical element, the field- and material free drift, can be applied to the map with the command

DL <length> ;

3.3.1 Multipoles

COSY supports magnetic and electric multipoles in a variety of ways. There are the following magnetic multipoles:

MQ <length> <flux density at pole tip> <aperture> ;

MH <length> <flux density at pole tip> <aperture> ;

MO <length> <flux density at pole tip> <aperture> ;

MD <length> <flux density at pole tip> <aperture> ;

MZ <length> <flux density at pole tip> <aperture> ;

which let a magnetic quadrupole, sextupole, octupole, decapole or duodecapole act on the map. The aperture is the distance from reference trajectory to pole tip. For the sake of speed, direct formulas for the aberrations are used for orders up to two. There is also a superimposed multipole for multipole strengths up to order five:

M5 <length> <BQ >< BH >< BO >< BD >< BZ> <aperture> ;

Output file fort.11 of a 3rd order calculation

Coordinates (final | initial)

final coordinates					initial coord.
x	a	y	b	l	xayblk
0.7084973	-0.179823	0.000000	0.000000	0.000000	100000
0.6952214	1.234984	0.000000	0.000000	0.000000	010000
0.000000	0.000000	1.234984	-0.1798231	0.000000	001000
0.000000	0.000000	0.695221	0.7084973	0.000000	000100
-0.755E-01	-0.51E-01	0.000000	0.000000	0.000000	300000
0.2751173	0.1728297	0.000000	0.000000	0.000000	210000
-0.4105720	-0.205759	0.000000	0.000000	0.000000	120000
0.3541071	0.813E-01	0.000000	0.000000	0.000000	030000
0.000000	0.000000	0.567E-01	-0.51E-01	0.000000	201000
0.000000	0.000000	-0.1303428	0.1142997	0.000000	111000
0.000000	0.000000	0.740E0-01	-0.678E-01	0.000000	021000
0.000000	0.000000	0.8969E-01	-0.746E-01	0.000000	200100
0.000000	0.000000	-0.2556298	0.1763417	0.000000	110100
0.000000	0.000000	0.3341813	-0.1293100	0.000000	020100
-0.788E-01	-0.55E-01	0.000000	0.000000	0.000000	102000
0.908E-01	0.600E-01	0.000000	0.000000	0.000000	012000
-0.2274343	-0.1568804	0.000000	0.000000	0.000000	101100
0.2605827	0.1763625	0.000000	0.000000	0.000000	011100
-0.1878345	-0.1152408	0.000000	0.000000	0.000000	100200
0.3370144	0.1287963	0.000000	0.000000	0.000000	010200
0.000000	0.000000	0.6003E-01	-0.555E-01	0.000000	003000
0.000000	0.000000	0.2715982	-0.2366632	0.000000	002100
0.000000	0.000000	0.4087833	-0.3485620	0.000000	001200
0.000000	0.000000	0.3568966	-0.1955448	0.000000	000300

Matrix elements (spelled out)

1st order

(x|x) (a|x) (y|x) (b|x) (l|x)
(x|a) (a|a) (y|a) (b|a) (l|a)
(x|y) (a|y) ….
(x|b) …..

3rd order

(x|xxx) (a|xxx) ….
(x|xxa)
(x|xaa)
(x|aaa)
(x|xxy) (a|xxyy) (y|xxy)
……

Example1_plot.fox

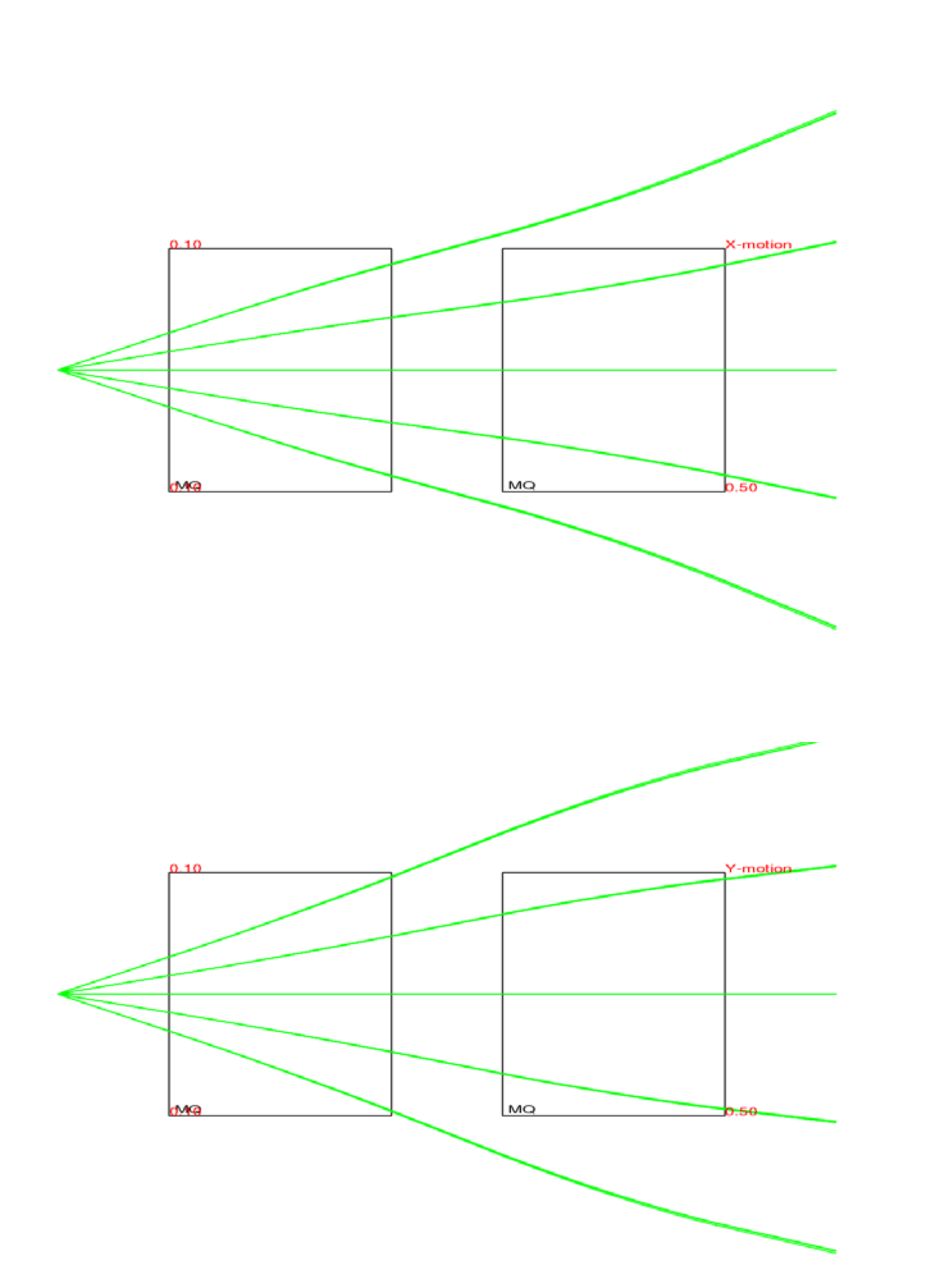
```
INCLUDE 'COSY' ;
PROCEDURE RUN ;
 OV 3 2 0 ; {order 3, phase space dim 2, # of parameters 0}
 RP 10 4 2 ; {kin. energy, mass 4 amu, charge 2}
 UM ; {sets maps to unity}

 SB 0.15 0.15 0 0.15 0.15 0 0 0 0 0 0 ;
 ER 1 5 1 5 1 1 1 1 ;
 BP ; {begins a picture}

 DL .1; {drift length .1 m}
 MQ .2 .1 .05; {quad, length .2 m, field 0.1 T, aperture .05 m}
 DL .1 ;{drift length .1 m}
 MQ .2 -.1 .05; {defoc. quad}
 Dl .1;{drift length .1 m}

 EP ; {ends a picture}
 PG -1 -2 ; {outputs x,y picture on screen, only for WINDOWS}
 PG -10 -10 ; {x,y picture as pic001.ps and pic002.ps, WINDOWS only}
{Use PG -12 -12 to create pdf file any operating system}
 PM 6 ; {prints Transfer Matrix on screen}
 PM 11 ;{prints Transfer Matrix to file fort.11}

ENDPROCEDURE ;
RUN ; END ;
```

The command

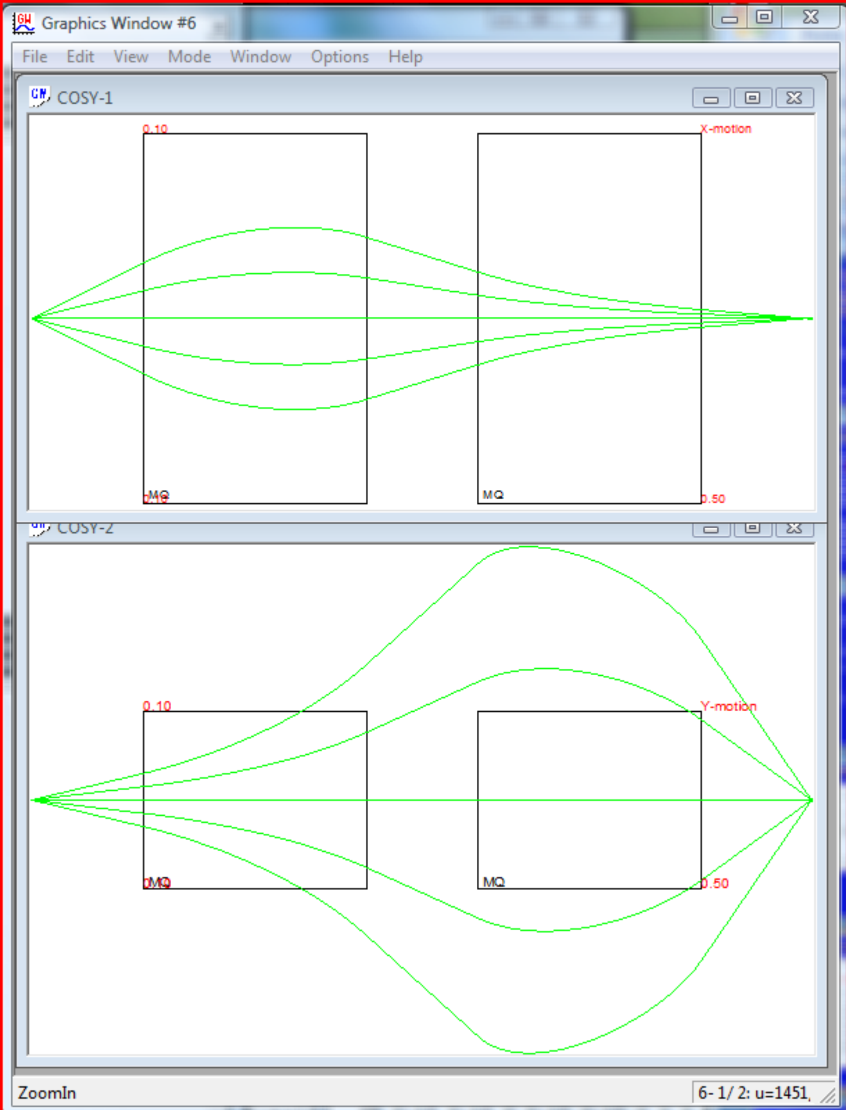
SB <PX><PA><r12><PY><PB><r34>< PT><PD><r56><PG><PZ> ;

sets half widths of the beam in the x, a, y, b, t, d, g and z directions of phase space as well as the off diagonal terms of the ellipse in TRANSPORT notation r12, r34, and r56. The units are meters for PX and PY, radians for PA and PB, $v_0\gamma/(1+\gamma)$ times time for PT, and $\Delta E/E$ for PD, $\Delta m/m$ for PG, and $\Delta z/z$ for PZ. The command

Picture of quad. doublet Q1,Q2 and 5 rays



- Q1 is horiz. (x) focusing
- Q1 is vert. (y) defocusing
- Q2 is horiz. defocusing
- Q2 is vert. defocusing
- Radius of both quads is 0.1 m
- ~ 0.15 rad rays pass through Q1
- ~ 0.15 rad rays do not pass Q2
- ~ 0.075 rad rays pass both quads
- The strength of the quads as given in the MQ command (0.1 T at radius 0.05 m) is too weak to focus the beam. Need more strength, e.g. 0.6 T.



Example1_Focus.fox
1st order calculation

Focus by adjusting quad. strengths

DL .1; {drift length .1 m}
MQ .2 1.225 .05; {length .2 m, 1.225 T, aperture .05 m}
DL .1 ;{drift length .1 m}
MQ .2 -1.23 .05; {defoc. quad}
Dl .1;{drift length .1 m}

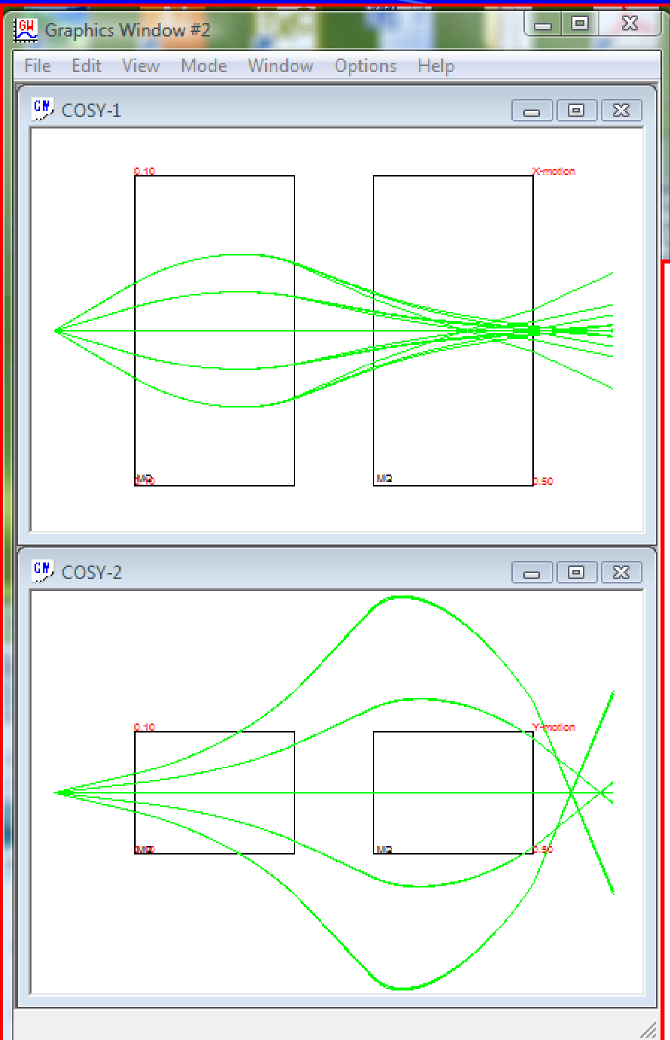
Unrealistic pole tip field > 0.8 T of normal conducting quadrupole!

Focus at the end of the system (focal plane)
(x|a) = R12 = 0 (small enough!)

Spacial and angle magnifications NOT 1

-6.090384	-26.15479	0.000000	0.000000	0.000000	100000
-0.000981	-0.168407	0.000000	0.000000	0.000000	010000
0.000000	0.000000	-0.197068	-26.16898	0.000000	001000
0.000000	0.000000	-0.007729	-6.100816	0.000000	000100

Example1_Focus.fox
3rd order calculation
150 mrad accptance is huge!



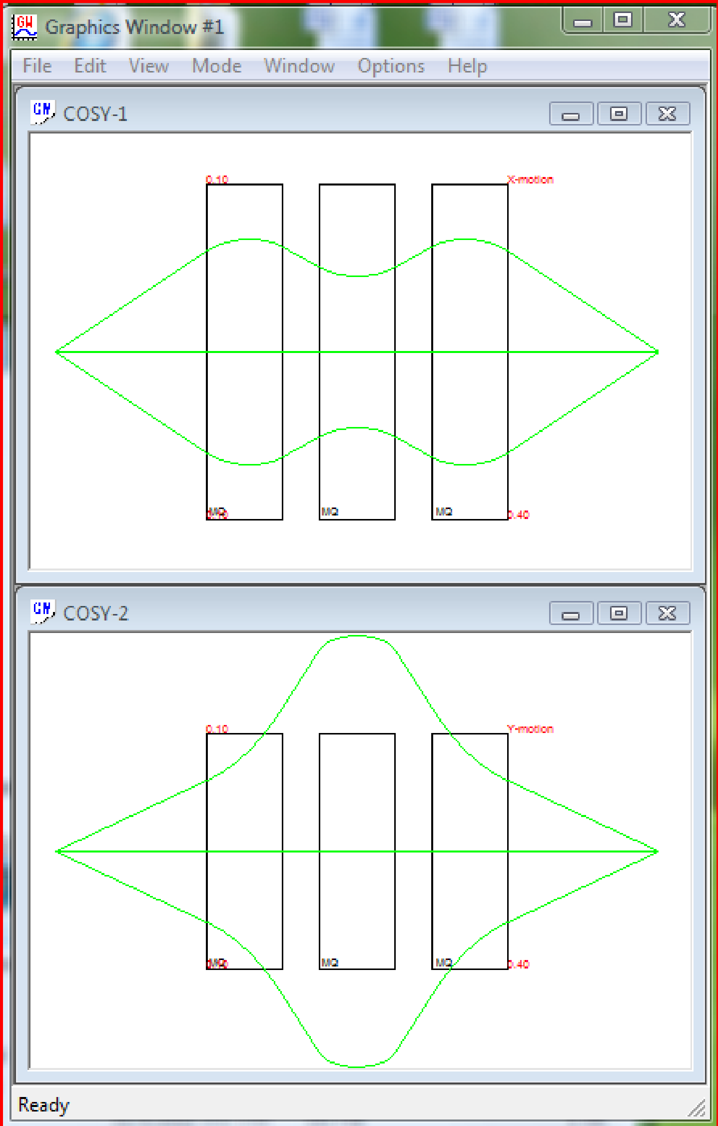
-6.090384	-26.15479	0.000000	0.000000	0.000000	100000
-0.9812817E-03	-0.1684073	0.000000	0.000000	0.000000	010000
0.000000	0.000000	-0.1970681	-26.16898	0.000000	001000
0.000000	0.000000	-0.7729611E-02	-6.100816	0.000000	000100
-1568.606	-1492.934	0.000000	0.000000	0.000000	300000
-74.43449	-190.2539	0.000000	0.000000	0.000000	210000
-2.546927	-8.910069	0.000000	0.000000	0.000000	120000
-0.4683690	-1.988386	0.000000	0.000000	0.000000	030000
0.000000	0.000000	-1226.485	7.198037	0.000000	201000
0.000000	0.000000	-23.21639	-55.58320	0.000000	111000
0.000000	0.000000	-0.3335998	-3.871998	0.000000	021000
0.000000	0.000000	-286.1340	-26.47701	0.000000	200100
0.000000	0.000000	-5.496428	-13.32838	0.000000	110100
0.000000	0.000000	-0.9693910E-01	-2.697014	0.000000	020100
-1785.252	-2396.501	0.000000	0.000000	0.000000	102000
-48.22888	-158.1376	0.000000	0.000000	0.000000	012000
-845.3337	-1173.046	0.000000	0.000000	0.000000	101100
-24.28755	-81.11583	0.000000	0.000000	0.000000	011100
-100.0870	-143.2272	0.000000	0.000000	0.000000	100200
-3.458532	-12.10800	0.000000	0.000000	0.000000	010200
0.000000	0.000000	-1337.345	-1479.809	0.000000	003000
0.000000	0.000000	-943.0241	-1195.555	0.000000	002100
0.000000	0.000000	-221.9257	-322.7006	0.000000	001200
0.000000	0.000000	-17.44606	-30.79001	0.000000	000300

-6.090384	-26.15479	0.000000	0.000000	0.000000	100000
-0.000981	-0.168407	0.000000	0.000000	0.000000	010000
0.000000	0.000000	-0.197068	-26.16898	0.000000	001000
0.000000	0.000000	-0.007729	-6.100816	0.000000	000100

Example2.fox Q-Triplet
Fit x and y focus

```
INCLUDE 'COSY' ;
PROCEDURE RUN ;
VARIABLE Q1 1 ; VARIABLE Q2 1 ; VARIABLE OBJ 1 ;
PROCEDURE TRIPLET A B ;
MQ .1 A .05 ; DL .05 ; MQ .1 -B .05 ; DL .05 ; MQ .1 A .05 ;
ENDPROCEDURE ;
OV 1 2 0 ; RP 1 1 1 ;
SB .15 .15 0 .15 .15 0 0 0 0 0 0 ; {sets half widths of beam .15 m in x, y and .15 rad in a, b}
Q1 := .5 ; Q2 := .5 ; {start values of Q1, Q2}
FIT Q1 Q2 ;
UM ; CR ; {clears the rays}
ER 1 3 1 3 1 1 1 1 ; {ensemble of rays, 3 in a, b}
BP ; {begins a picture}
DL .2 ; TRIPLET Q1 Q2 ; DL .2 ;
EP ; {ends the picture}
PG -1 -2 ; {outputs the x,y pictures to default windows}
OBJ := ABS(ME(1,2))+ABS(ME(3,4)) ; {defines the objective OBJ.
ME(1,2): map element (x,a), ME(3,4): map element (y,b)}
WRITE 6 'Q1, Q2: ' Q1 Q2 'OBJECTIVE: ' OBJ ;
ENDFIT 1E-5 1000 1 OBJ ; {fits OBJ by Simplex algorithm. This is point-to-point for both x, y}
PG -10 -10 ;  {output final pictures to PostScript files pic001.ps and pic002.ps}
PM 11 ;  {Prints Transfer Matrix to file fort.11}
ENDPROCEDURE ;
RUN ; END ;
```

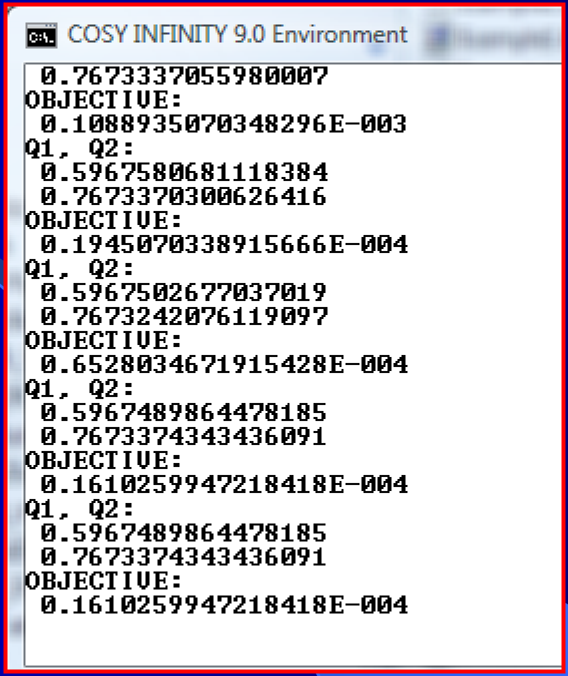
Result of Q-Triplet fit



On screen:
← Picture of rays

Quad. Strengths Q1,Q2
and fit objectives →

Final Q1,Q2 →



```
COSY INFINITY 9.0 Environment
 0.7673337055980007
OBJECTIVE:
 0.1088935070348296E-003
Q1, Q2:
 0.5967580681118384
 0.7673370300626416
OBJECTIVE:
 0.1945070338915666E-004
Q1, Q2:
 0.5967502677037019
 0.7673242076119097
OBJECTIVE:
 0.6528034671915428E-004
Q1, Q2:
 0.5967489864478185
 0.7673374343436091
OBJECTIVE:
 0.1610259947218418E-004
Q1, Q2:
 0.5967489864478185
 0.7673374343436091
OBJECTIVE:
 0.1610259947218418E-004
```

Focus at the end of the system (focal plane)
(x|a) = R12 = 0 (small enough!)

1st order matrix in file fort.11

-1.000001	1.175777	0.000000	0.000000	0.000000	100000
0.000002	-1.000001	0.000000	0.000000	0.000000	010000
0.000000	0.000000	-1.000044	-6.471740	0.000000	001000
0.000000	0.000000	-0.000014	-1.000044	0.000000	000100

\---

Spacial and angle magnifications are 1
ONE-TO-ONE transportation

COSY calculation for the St. George Recoil Separator

Files needed (in a COSYfied folder):

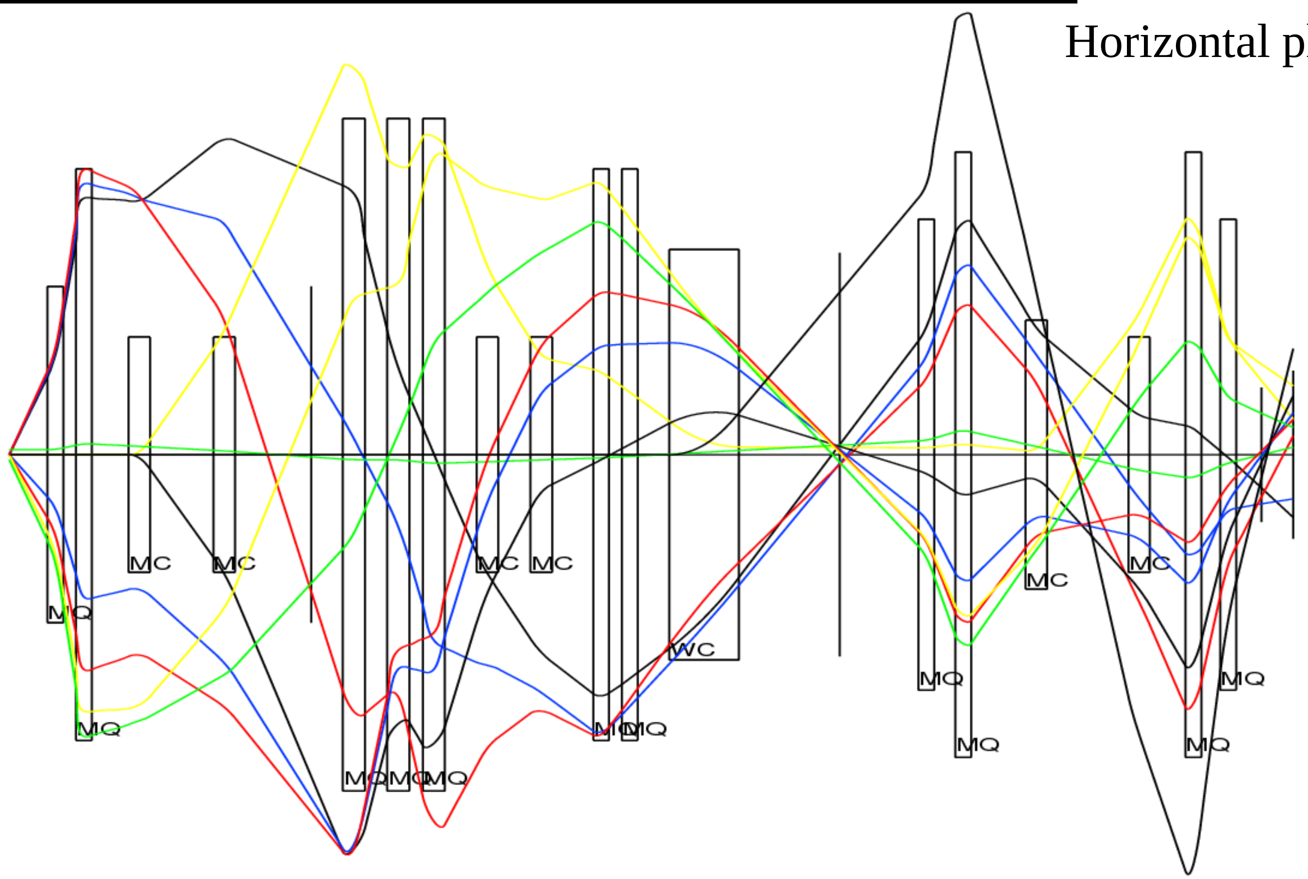
- clean_figx.fox - COSY input *.fox file with final (optimized) ion-optics and 11 characteristic rays and the discarded beam
- SYSCA.DAT - Input file for fringe fields
- drift.txt - input file with drift lengths
- fields.txt - input file with quadrupole strengths
- quadlengths.txt – input file with quadrupole lengths
- dipole.txt – input file with dipole strengths

Output files:

- pic0001.ps - Picture of rays in x-plane
- pic0002.ps - Picture of rays in y-plane

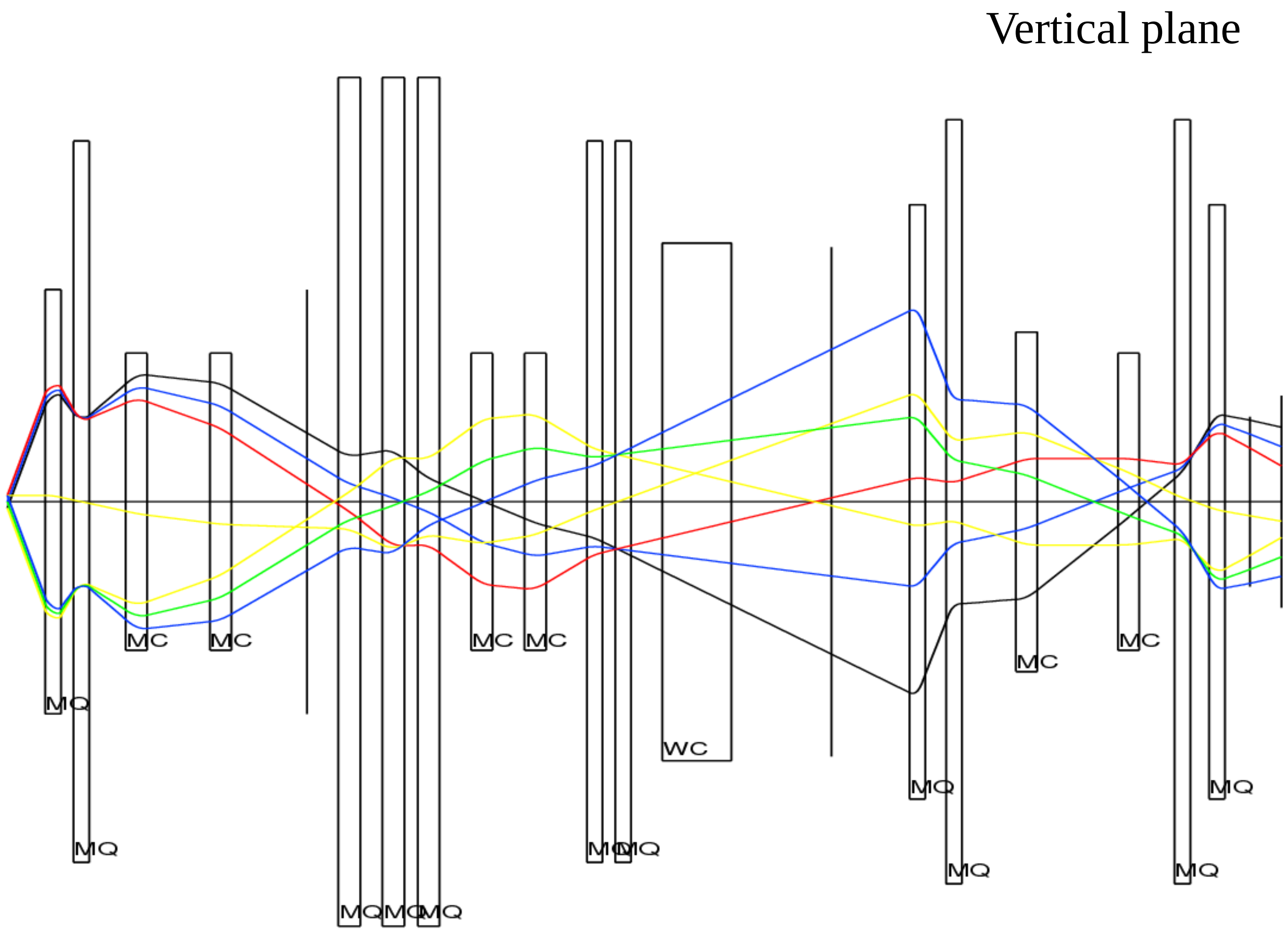
St. George Astrophysics Recoil Separator 3rd Order COSY calculation

	x	a	y	b	t	dK	dm	dz		
SR	0.0	0.04	0.0	0.0	0.0	0.075	0.0	0.0	1	;{Ray 1}
SR	0.0	0.04	0.0	0.0	0.0	0.00	0.0	0.0	2	;{Ray 2}
SR	0.0	0.04	0.0	0.0	0.0	-0.075	0.0	0.0	3	;{Ray 3}
SR	0.0	0.0	0.0	0.0	0.0	0.13	0.0	0.0	4	;{Ray 4}
SR	0.0015	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5	;{Ray 5}
SR	0.0	0.0	0.0	0.0	0.0	-0.105	0.0	0.0	1	;{Ray 6}
SR	0.0	-0.02	0.0	0.0	0.0	-0.095	0.0	0.0	2	;{Ray 7}
SR	0.0	-0.03	0.0	0.0	0.0	-0.09	0.0	0.0	3	;{Ray 8}
SR	0.0	-0.04	0.0	0.0	0.0	0.075	0.0	0.0	4	;{Ray 9}
SR	-0.0015	-0.04	0.0	0.0	0.0	0.0	0.0	0.0	5	;{Ray 10}
SR	0.0	0.0	0.0	0.0	0.0	0.1	-0.090909	0.0	1	;{Beam}

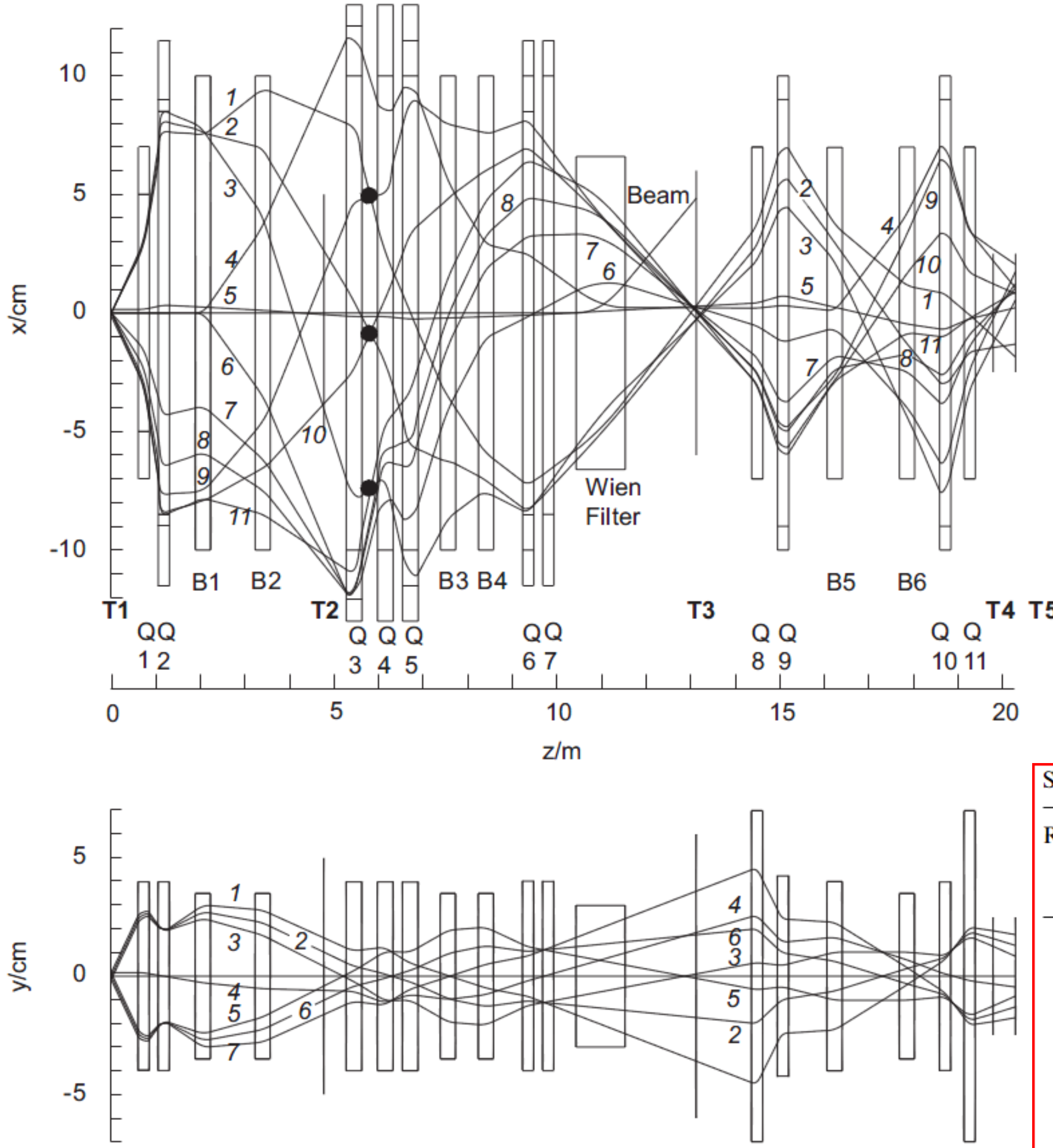


Horizontal plane

St. George, vertical plane



Presentation and discussion of the characteristic rays defining the ion-optics of the St. George Recoil Separator

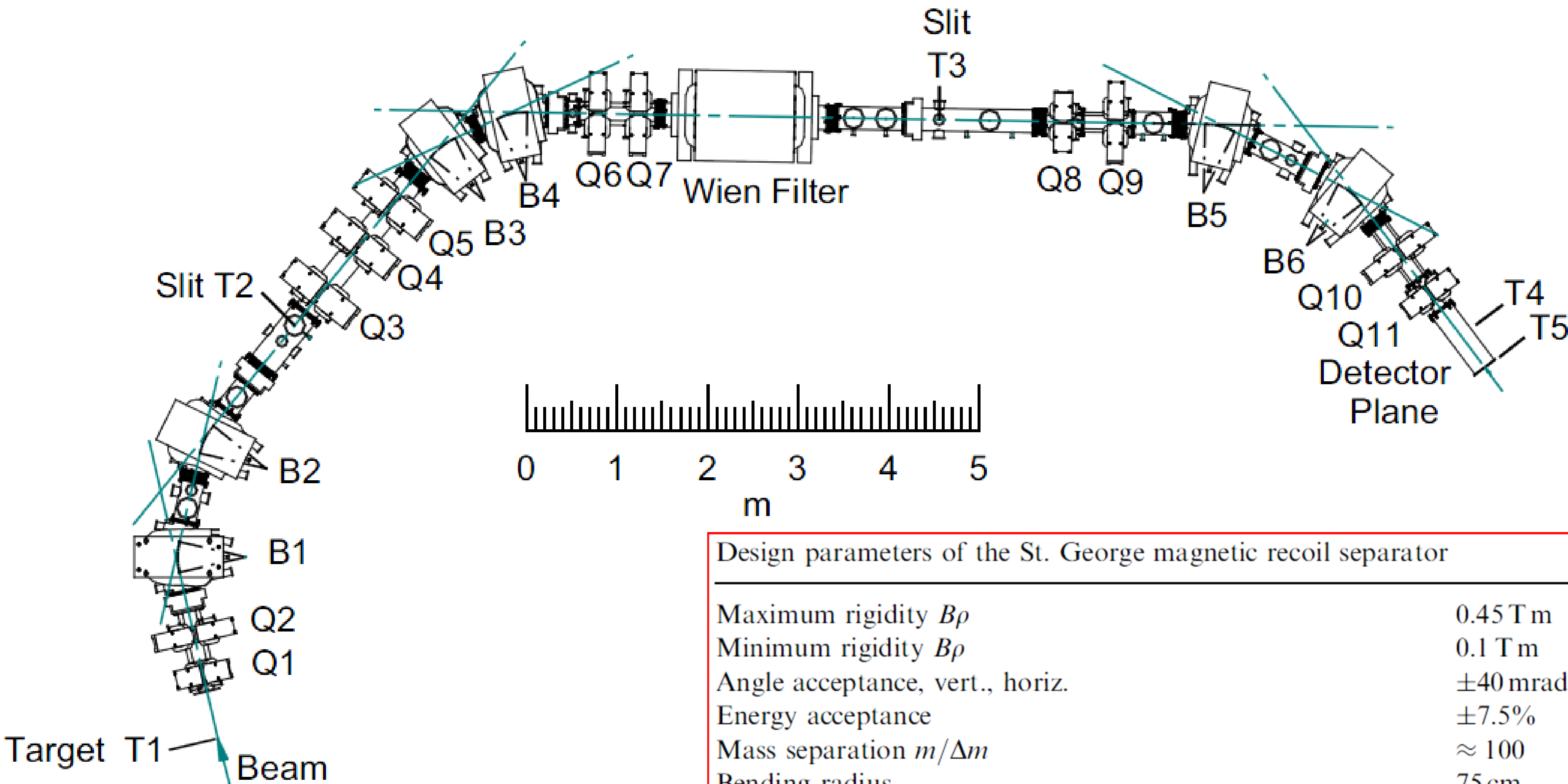


. Ion optics of the St. George recoil separator. The starting values of the rays are listed in Table 3. For

Starting values of the 11 horizontal and 7 vertical rays shown in Fig. 2

Ray number	Horizontal rays			Vertical rays	
	x (mm)	Θ (mrad)	$\delta E/E$ (%)	y (mm)	Φ (mrad)
1	0	40	7.5	−1.5	40
2	0	40	0	0	40
3	0	40	−7.5	1.5	40
4	0	0	13	1.5	0
5	1.5	0	0	1.5	−40
6	0	0	−10.5	0	−40
7	0	−20	−9.5	−1.5	−40
8	0	−30	−9.0		
9	0	−40	7.5		
10	1.5	−40	0		
11	0	−40	−7.5		
Beam	0	0	0		

Layout and magnet design of the St. George Recoil Separator based on the ion-optical calculations



Design parameters of the St. George magnetic recoil separator	
Maximum rigidity $B\rho$	0.45 T m
Minimum rigidity $B\rho$	0.1 T m
Angle acceptance, vert., horiz.	±40 mrad
Energy acceptance	±7.5%
Mass separation $m/\Delta m$	≈ 100
Bending radius	75 cm

Fig. 1. Layout of the St. George recoil separator.

TRANSPORT

TRANSPORT was one of the early ion-optical codes mainly for beam lines (1st and 2nd order only). It is very well documented and a great resource for simple optics and an Appendix with articles for deeper insight into ion-optics.

TRANSPORT, A Computer Program for Designing Charged Particle Beam Transport Systems, K.L. Brown, D.C. Carey, Ch. Iselin, F. Rotacker, Report CERN 80-04, Geneva, 1980

Modern version with graphics interface developed by Urs Rohrer, PSI, and available online at:

http://aea.web.psi.ch/Urs_Rohrer/MyWeb/trans.htm