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Ray-tracing tutorial

F. Meot

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Collider-Accelerator Department

Brookhaven National Laboratory

U.S. Department of Energy
DOE Office of Science

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François Méot
BNL, C-AD, Upton, NY

RAY-TRACING TUTORIAL

FFAG 2012 School

Kyoto University Research Reactor Institute
11-12 November 2012

INTRODUCTION

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1 Goal of the exercises

Produce machine parameters, perform beam dynamics simulations, using stepwise ray-tracing means, namely, the ray-tracing code Zgoubi.

The exercises focus on the 150 MeV FFAG operated at KEK in the mid-2000, a machine with specifications very close to the present KURRI ADS-Reactor R&D 150 MeV FFAG ring.

During the exercises planned, as much as time allows, we will

- **find orbits, check magnetic field on orbits,**
- **find tunes, betatron functions, chromaticities, acceleration frequency law, etc.**
- **perform a full acceleration cycle,** $12 \rightarrow 150$ **MeV, 15000 turns about**
- **use FFAG keyword in Zgoubi**
- **use the OPERA field maps of the 150 MeV FFAG triplet magnet, by means of the TOSCA keyword in Zgoubi**
- **compare fields in the hypothesis of magnet model with either 3 dipoles or 5 dipoles**

During the exercises, it is strongly recommended to have a compendium of formulæ at hand : earlier lecture by Mike Craddock.

In that way we can check the constistency of the numerical results we get during the exercises, a warmly recommended general attitude, regarding numerical simulations.

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2 Working hypotheses, 150 MeV FFAG

The hypotheses below hold for the all series of exercises.

Main parameters :

$E_{inj} - E_{max}$	**MeV**	**12 - 150**
orbit radius	**m**	**4.47 - 5.20**
lattice / K		**DFD $\times$ 12 / 7.6**
β_r / β_z **max.**	**m**	**2.5 / 4.5**
ν_r / ν_z		**3.7 / 1.3**
B_D / B_F	**T**	**0.2-0.78 / 0.5-1.63**
gap	**cm**	**23.2 - 4.2**
RF swing	**MHz**	**1.5 - 4.5**
voltage p-to-p	**kV**	**2**
rep. rate	**Hz**	**250**

Triplet magnet

150 MeV FFAG

First beam 2003. Reached 100 MeV at full ΔR

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3 Numerical simulation tools - Zgoubi ray-tracing code

The Zgoubi package is provided. It contains

- **the ray-tracing code zgoubi (sources and executable in []/tutorial/zgoubiPackage/zgoubi/)**
- **the graphic/analysis postprocessor, zpop (sources and executable in []/tutorial/zgoubiPackage/zpop/).**

  Note : zpop execution must be launched from an xterm window
- **Zgoubi users' guide (in []/tutorial/zgoubiPackage/doc/)**
- **tool-kits proper to the design of periodic machines and FFAGs (in []/tutorial/zgoubiPackage/tools/)**

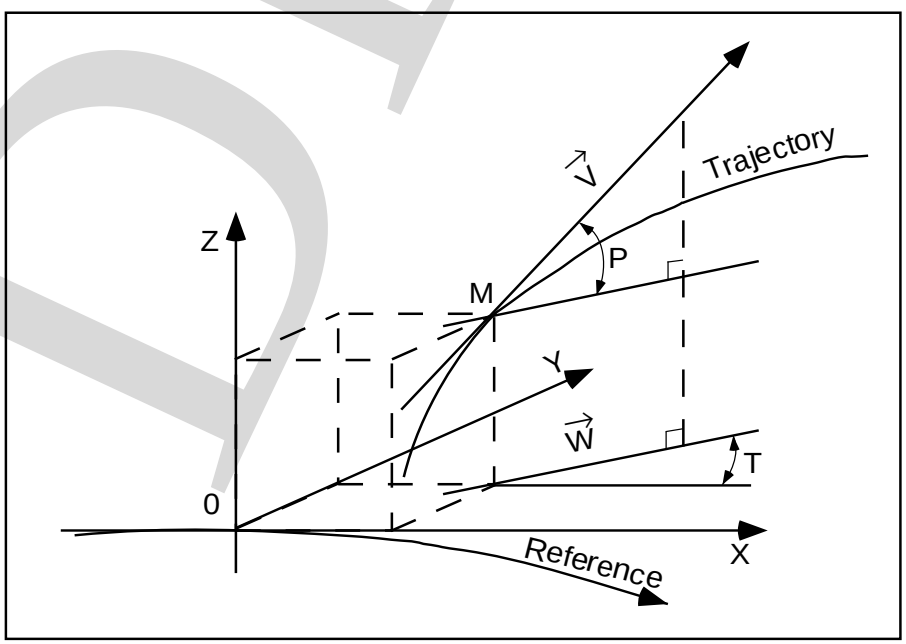
In addition a few articles that address the topics will we work on can be found in []/tutorial/zgoubiPackage/bibliography/.

For more information on Zgoubi, see the development web site

http://sourceforge.net/projects/zgoubi/

Many additional examples of applications can be found there, as well as in the guide : synchrotron radiation at LHC, polarized beams at RHIC, muon acceleration and decay in the Neutrino Factory, etc..

Motion frame and particle coordinates in Zgoubi



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The exercises proposed rely upon a variety of concepts and works, that have been subject to publication. A (non-exhaustive) list of readings of interest is proposed below.

References

[1] 150 MeV FFAG Design, Construction, Commissioning Studies, Y. Mori et al., PAC and EPAC Conference Proceedings, http://www.jacow.org/

[2] FFAG Workshops, FFAG synchrotron Home Page, http://hadron.kek.jp/FFAG/

[3] *Zgoubi users' guide,* F. Méot Tech. Note BNL C-AD/AP/470 (2012).

[4] *A numerical method for combined spin tracking and raytracing of charged particles,* F. Méot, NIM A313 (1992) 492, and proc. EPAC (1992) p.747.

[5] *Implementation of a coupled treatment of the one-turn mapping in the ray-tracing code Zgoubbi,* F. Desforges, C-AD Note C-A/AP/461, BNL, Sept 2012.

[6] *Deflecting magnets,* in Focusing of Charged Particles, H.A. Enge, ed. A. Septier, Vol. II, pp 203-264, Academic Press Inc., 1967.

[7] *Developements in the ray-tracing code Zgoubi for 6-D multiturn tracking in FFAG rings,* F. Lemuet, F. Méot, NIM A 547 (2005) 638-651.

[8] *6-D beam dynamics simulations in FFAGs using the ray-tracing code Zgoubi,* F. Méot, ICFA Beam Dyn.Newslett.43:44-50 (2007).

[9] *Collection and muon acceleration in the neutrino factory project,* Franck Lemuet, PhD thesis, Paris KI University, April 2007.

[10] *Acceleration in the linear non-scaling fixed-field alternating-gradient accelerator EMMA,* S. Machida et al., Nature Physics, vol. 8, March 2012.

[11] *Spiral FFAG lattice design tools, application to 6-D tracking in a proton-therapy class lattice,* J. Fourrier, F. Martinache, F. Méot, J. Pasternak, NIM A 589 (2008).

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François Méot
BNL C-AD, Upton, NY

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EXERCISE #1

- Orbits and Field -

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1 Goal of the exercise

- **Find the orbit for a given momentum**
- **Check the magnetic field on that orbit**
- **Check the scalloping, its amplitude**
- **For that orbit, get the tunes, betatron amplitudes, either**
  - **using the `MATRIX` keyword in Zgoubi**
  - **doing multi-turn tracking**

Recommendations

In the exercise directory, you'll find a "workFiles" directory which contains the input data files to Zgoubi for the exercise, and a "workSpace" directory.

It is stronly encouraged to leave "workFiles" untouched, and work in "workSpace" rather, using the files copied from "workFiles".

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2 Finding field, orbits, optical parameters

• The 150 MeV FFAG is a scaling lattice, the field law in both F and D dipole components of the DFD triplet satisfies

$$\frac{B}{B_0} = \left(\frac{r}{r_0}\right)^K$$

• Now, introducing

$$B\rho = \frac{p}{q}$$

and assuming that the packing factor is about constant, by what we mean

$$\frac{r}{\rho} \approx \frac{r_0}{\rho_0}$$

(in practice the orbit scallops, however that effect is of the order of a few % of the average radius, we will be able to check that from the tracking), then the following relationships between radius and momentum, or radius and kinetic energy E, come out

$$\frac{r}{r_0} = \left(\frac{p}{p_0}\right)^{\frac{1}{K+1}}, \quad \frac{r}{r_0} = \left(\frac{E(E+2m)}{E_0(E_0+2m)}\right)^{\frac{1}{2(K+1)}}$$

• This tells us approximately where the orbit has to be found.

Inpout data for Zgoubi :

For E=12 MeV, proton, m = 938.272 MeV, the formula on the left yields

$$r_{CO} \approx 4.52 \text{ m}$$

For E=150 MeV,

$$r_{CO} \approx 5.32 \text{ m}$$

On the other hand, the particles are launched at the center of the drift between two triplets. As a consequence, for all,

$$r_0' = 0$$

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(i) Now, using closedOrbit.fai.dat (namely, copy []/workFiles/closedOrbit.fai.dat to []/workSpace/zgoubi.dat), launch a 12 MeV particle. Find (r_{CO}, r'_{CO}) from multi-turn tracking.

Next, do the same for a 150 MeV particle.

Hints :

1/ Check in Zgoubi users' Guide as to the use of the keyword `FAISTORE` and of the [b_]zgoubi.fai storage file, that you'll find declared in zgoubi.dat.

2/ Plot the horizontal phase-space using zpop (first, options 7/2 in zpop menu, and chose coordinates Y, T ; then option 7/1 to open file b_zgoubi.fai, followed by option 7/7 to plot).

Reminder : ([...]/zgoubiPackage/zpop/zpop must be launched in an xterm window.

Ans. :

It will be noticed that, due to the tune close to third integer, one has to be rather close to the final r_{co} in order for the particle to survive a large number of turns.

For that reason we start with (Zgoubi's Y : radial coordinate) $Y = 440$ cm (12 MeV) and $Y = 520$ cm (150 MeV).

Given this precaution, after a few iterations, one finds :

- At 12 MeV, we find $r_{CO} \approx 4.45$ m, 1.5% below the theoretical value
- At 150 MeV, we find $r_{CO} \approx 5.17$ m, 2.8% below the theoretical value

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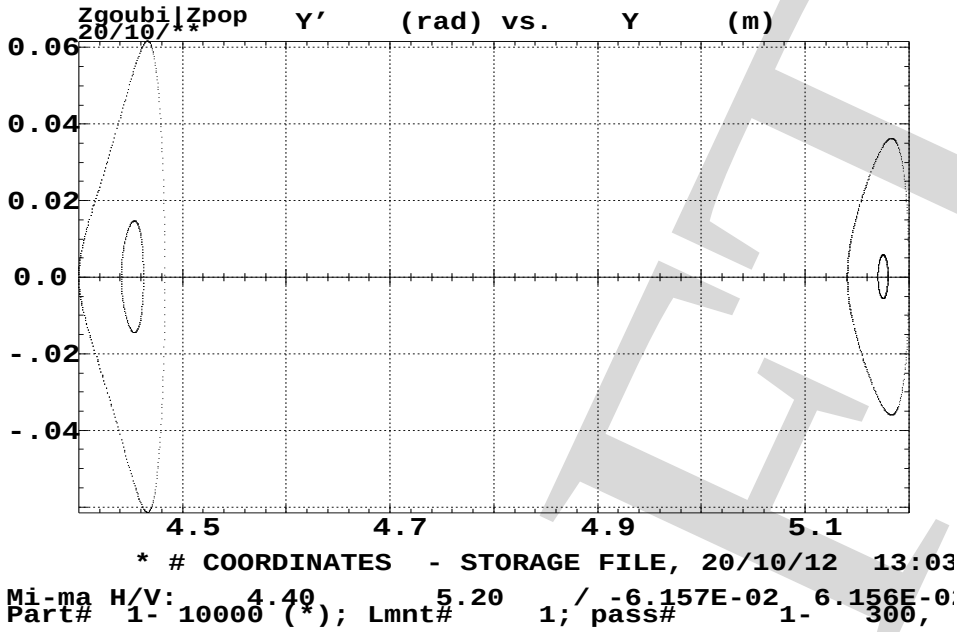
Zgoubi|Zpop
20/10/**
Y' (rad) vs. Y (m)
0.06
0.04
0.02
0.0
-.02
-.04
4.5
4.7
4.9
5.1
* # COORDINATES - STORAGE FILE, 20/10/12 13:03
Mi-ma H/V: 4.40 5.20 / -6.157E-02 6.156E-0
Part# 1- 10000 (*); Lmnt# 1; pass# 1- 300,

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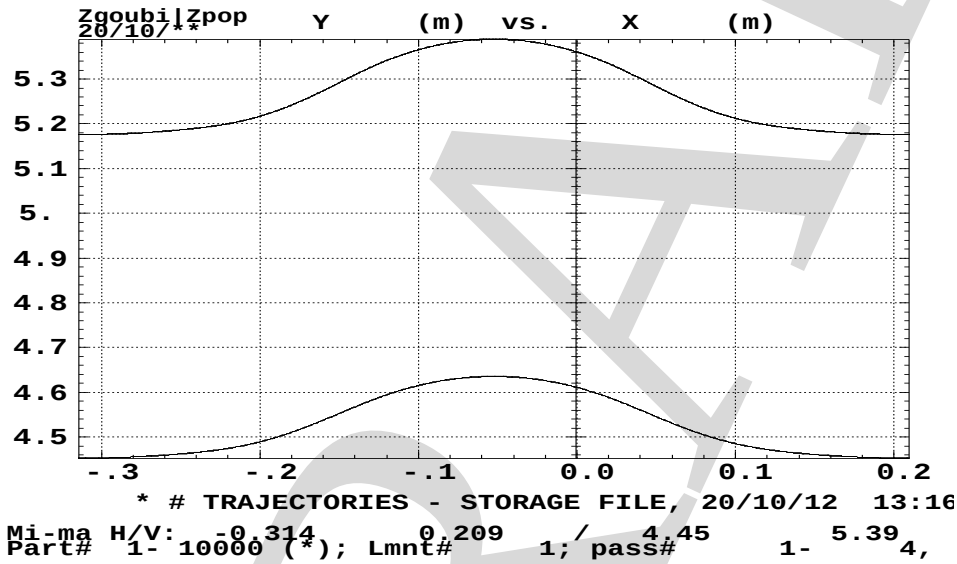
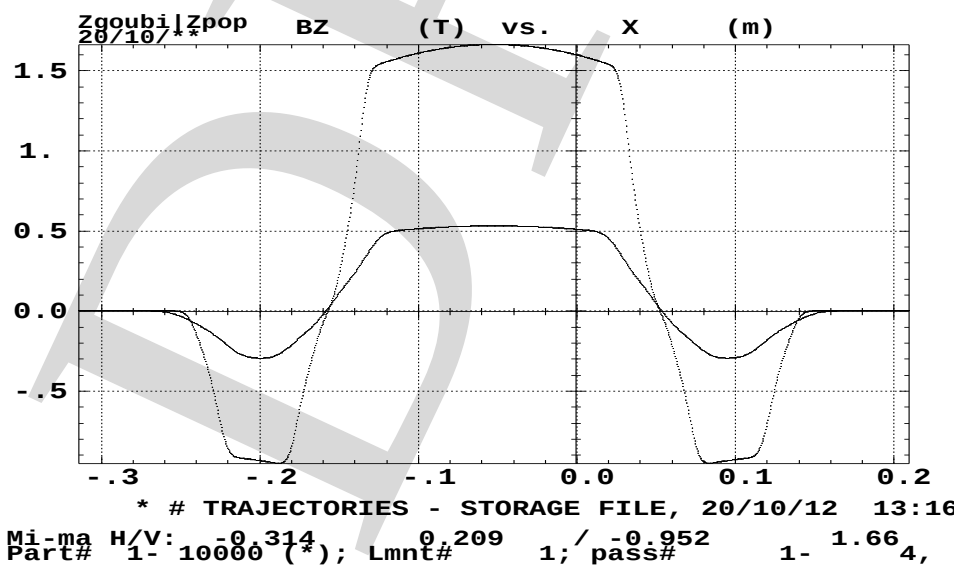
(ii) Now, using closedOrbit.plt.dat (namely, copy []/workFiles/closedOrbit.plt.dat to []/workSpace/zgoubi.dat),

(a) plot the orbit over a cell (first, option 7/2 in zpop menu, and chose coordinates X, Y ; then option 7/1 to open file zgoubi.plt, followed by option 7/7 to plot).

(b) Plot the field on the orbit (first, option 7/2 and chose coordinates X, B ; then option 7/1 to open file zgoubi.plt, followed by option 7/7 to plot),

Ans. :





It can be seen from the figure above, that the field in the drift is zero. This does

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not strictly reflect reality. It will be seen from the OPERA map, later in the course, that the field in the drift, in the absence of field clamps, is a few hundred Gauss. This is better simulated if the "`FFAG`" keyword describes a 5-tuplet rather than the present 3-tuplet, this will be addressed as well, later.

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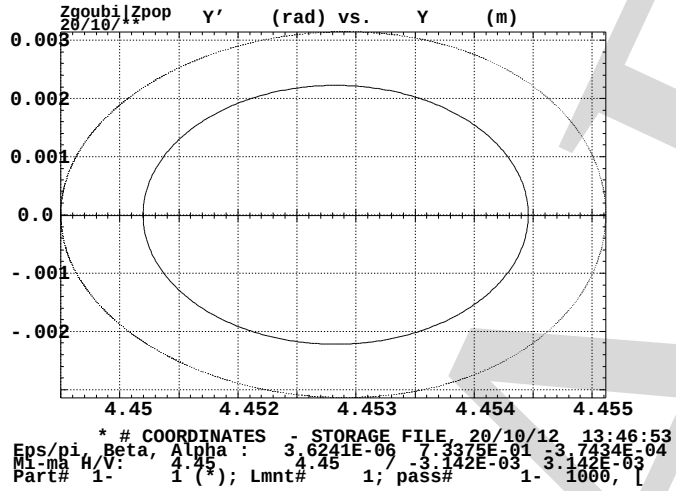
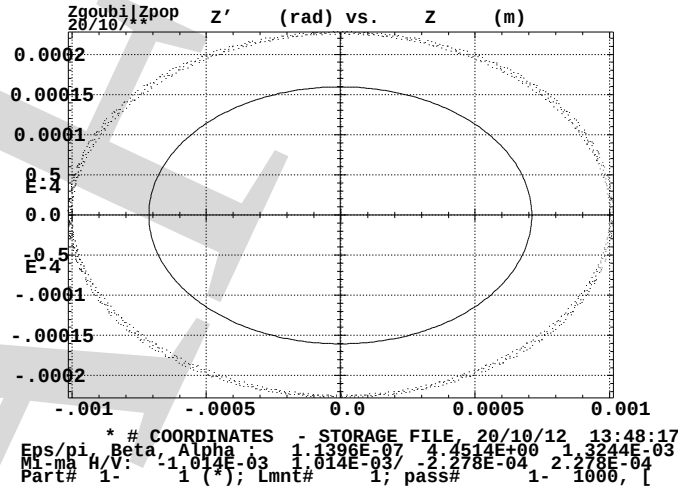
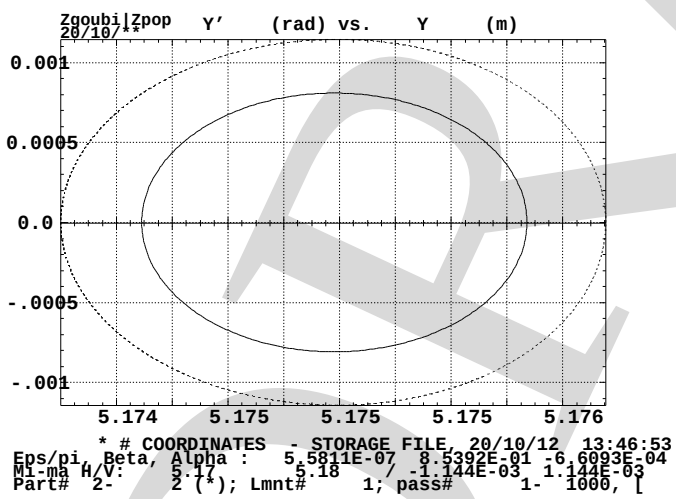
(iii) Using multiturn.dat, track a paraxial particle, with non-zero radial and axial motions, for 1000 turns or so (much less would do as well)

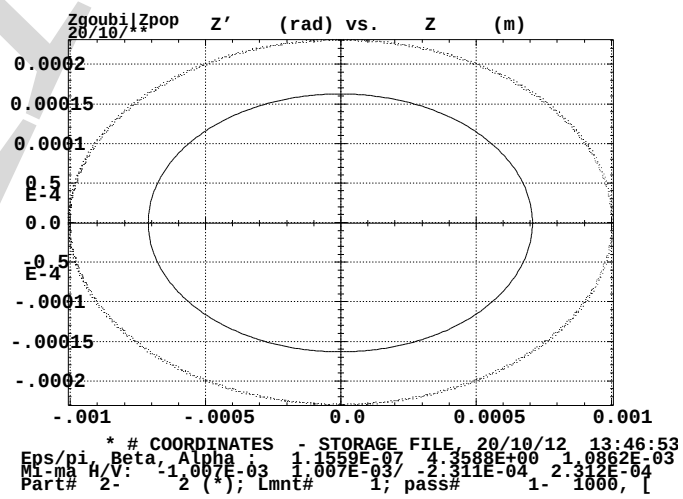
(a) Using zpop, plot the the (r,r') and (y,y') phase spaces.
Get the betatron function values, β_r, β_y, at the center of the drift

Ans. :









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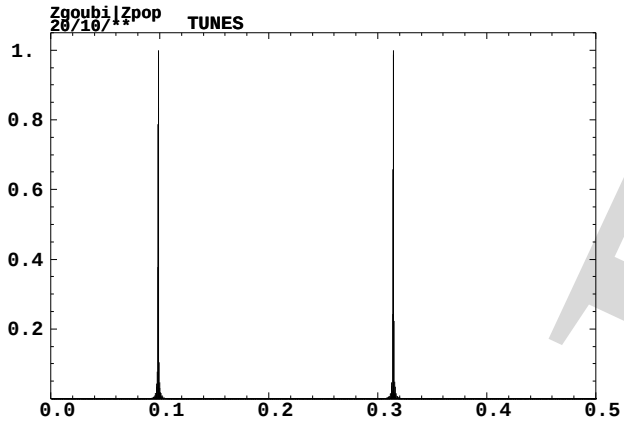
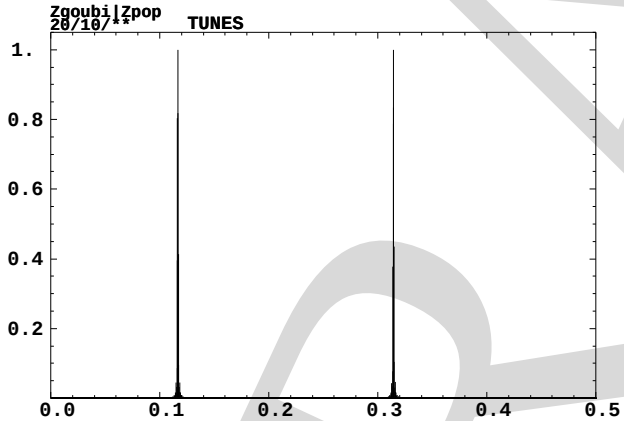
(b) Find the tunes from Fourier analysis (option 8/13 in zpop menu)

Ans. :



NuZ = 0.098641 amplitude = 0.2534
NuY = 0.314241 amplitude = 1.268
Part 1 at Lmnt 1 to *****



NuZ = 0.116630 amplitude = 0.2519
NuY = 0.314391 amplitude = 0.2380
Part 2 at Lmnt 1 to *****

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(iv) Using files twiss_12MeV.dat and twiss_150MeV.dat from "workFiles", find the tunes and chromaticities

Ans. :

Found at the end the zgoubi.res file, case of 12 MeV case :

```
   6  Keyword, label(s) :  TWISS

 Reference, absolute (part #1) : -7.2695E-01 4.4523E+02 2.7104E-04 0.0  0.0 2.4116E+02  8.0444E-

         Frame for MATRIX calculation moved by :
     XC =    0.000 cm , YC =  445.234 cm ,   A =  0.00002 deg  ( = 0.000000 rad )


 Reference particle (#   1), path length :   241.16510     cm  relative momentum :   0.273043


                TRANSFER  MATRIX  ORDRE  1  (MKSA units)

 -0.392693        0.675612         0.00000         0.00000         0.00000         0.716649
 -1.25189       -0.392693         0.00000         0.00000         0.00000         0.644194
  0.00000         0.00000        0.814072         2.58596         0.00000         0.00000
  0.00000         0.00000       -0.130430        0.814072         0.00000         0.00000
 0.644181        0.716633         0.00000         0.00000         1.00000       -5.144766E-02
  0.00000         0.00000         0.00000         0.00000         0.00000         1.00000

     DetY-1 =       0.0000000291,    DetZ-1 =       0.0000001142

        R12=0 at    1.720     m,        R34=0 at   -3.177     m

    First order symplectic conditions (expected values = 0) :
:
      2.9134E-08    1.1418E-07     0.000         0.000         0.000         0.000


             TWISS  parameters,  periodicity  of   1  is  assumed :

     Beam  matrix  (beta/-alpha/-alpha/gamma) and  periodic  dispersion  (MKSA units)

         0.734625     0.000000     0.000000     0.000000     0.000000     0.514578
         0.000000     1.361239     0.000000     0.000000     0.000000     0.000000
         0.000000     0.000000     4.452684     0.000000     0.000000     0.000000
         0.000000     0.000000     0.000000     0.224584     0.000000     0.000000
         0.000000     0.000000     0.000000     0.000000     0.000000     0.000000
         0.000000     0.000000     0.000000     0.000000     0.000000     0.000000

                                Betatron  tunes

                 NU_Y =  0.31422821         NU_Z =  0.98623065E-01

                       ****  End  of  'TWISS'  procedure  ****

    There  has  been          3  pass  through  the  optical  structure


                                Momentum compaction :

                            dL/L / dp/p =  5.93254647E-02
```

```
Transition gamma  =   4.1056264

Chromaticities :

dNu_y / dp/p = -0.90452175
dNu_z / dp/p = -0.83415010
```

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Found at the end the zgoubi.res file, 150 MeV case :

```
    6  Keyword, label(s) :  TWISS

Reference, absolute (part #   1)  :  -5.2E-07  5.1749E+02  3.6959E-04  0.0E+00  0.0E+00  2.8042

         Frame for MATRIX calculation moved by :
          XC =    0.000 cm , YC =  517.498 cm ,   A =  0.00002 deg  ( = 0.000000 rad )

Reference particle (#   1), path length :   280.42632     cm  relative momentum :   0.999999

                TRANSFER  MATRIX  ORDRE  1  (MKSA units)

-0.393625        0.785146         0.00000         0.00000         0.00000        0.837041
-1.07631        -0.393625         0.00000         0.00000         0.00000        0.646453
 0.00000         0.00000         0.743315         2.91590         0.00000         0.00000
 0.00000         0.00000        -0.153463        0.743315         0.00000         0.00000
 0.646452        0.837039         0.00000         0.00000         1.00000       -6.232088E-02
 0.00000         0.00000         0.00000         0.00000         0.00000         1.00000

        DetY-1 =       0.0000000254,    DetZ-1 =       0.0000001139

        R12=0 at    1.995     m,        R34=0 at   -3.923     m

    First order symplectic conditions (expected values = 0) :
       2.5367E-08    1.1388E-07     0.000         0.000         0.000         0.000

             TWISS  parameters,  periodicity  of   1  is  assumed :

     Beam  matrix  (beta/-alpha/-alpha/gamma) and  periodic  dispersion  (MKSA units)
         0.854097     0.000000     0.000000     0.000000     0.000000     0.600621
         0.000000     1.170828     0.000000     0.000000     0.000000     0.000000
         0.000000     0.000000     4.358977     0.000000     0.000000     0.000000
         0.000000     0.000000     0.000000     0.229412     0.000000     0.000000
         0.000000     0.000000     0.000000     0.000000     0.000000     0.000000
         0.000000     0.000000     0.000000     0.000000     0.000000     0.000000

                         Betatron  tunes
                NU_Y =  0.31438963         NU_Z =  0.11662629

                         Momentum compaction :
                       dL/L / dp/p =  0.11623474

                         Transition gamma  =   2.9331348

                         Chromaticities :
                       dNu_y / dp/p =  6.56033206E-05
                       dNu_z / dp/p =  8.62418854E-03
```

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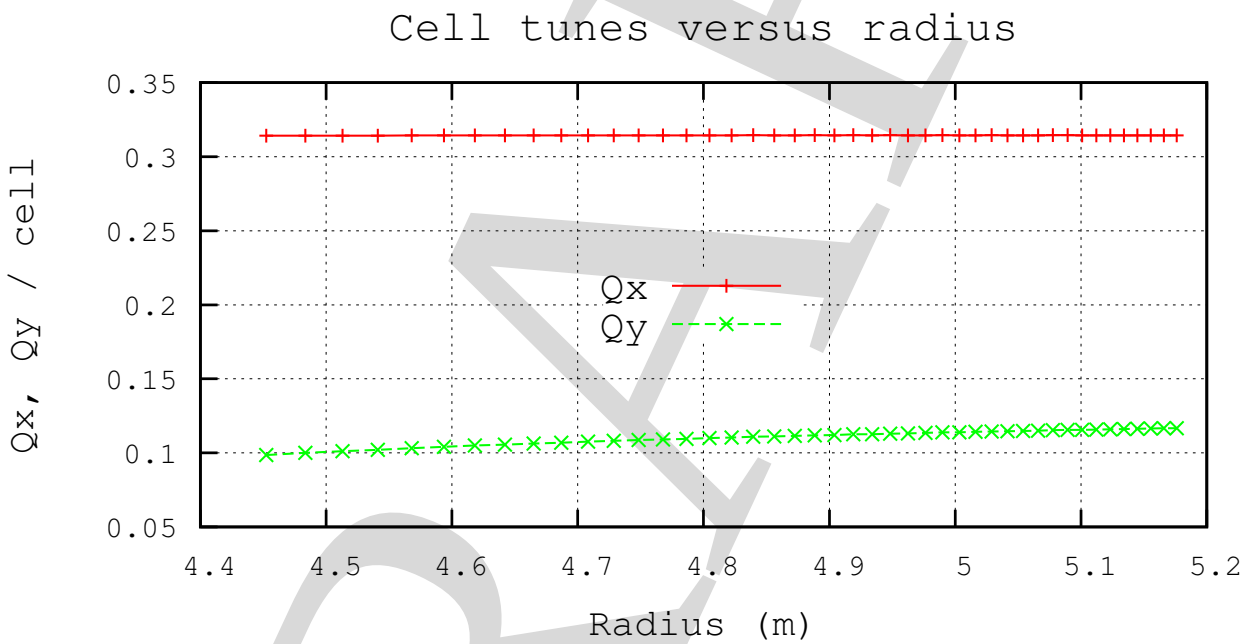
3 Complements

In the toolbox, [..]/tools/tunesFromFai/, one can find the program "tunesFromFai[.f]". This will compute the tunes, from the "b_zgoubi.fai" resulting from the tracking of one or more particles over a few hundred turns, as in

[]workFiles/closedOrbit_44traj.dat.

Using gnuplot (and, e.g., []workFiles/gnuplot_tunesFromFai.cmd), it is then easy to obtain such plot as below.



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François Méot
BNL C-AD, Upton, NY

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EXERCISE #2

- More on betatron functions -

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1 Goal of the exercise

In this exercise we will do a scan of the betatron function values in the drift, over the radial range $12 \rightarrow 150$ MeV.

We will discuss their transport through the cell.

Recommendations

In the exercise directory, you'll find a "workFiles" directory which contains the input data files to Zgoubi for the exercise, and a "workSpace" directory.

It is stronly encouraged to leave "workFiles" untouched, and work in "workSpace" rather, using the files copied from "workFiles".

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2 Setting up files for beta scan

(i) Copy []/3.exercise#2_opticalFunctions/workFiles/zgoubi_searchCO-In.dat and []/3.exercise#2_opticalFunctions/workFiles/searchCO.data to []/3.exercise#2_opticalFunctions/workSpace.

Copy also searchCO.data, the input data to zgoubi_searchCO-In.dat.

(ii) Then run tutorial/tools/searchClosedOrbit/searchCOs_From1Traj.
Note : you may have to change the address of the executable in searchCOs_From1Traj.f (now it is '../../zgoubiPackage/zgoubi/zgoubi').

How that works : the input file searchCO.data to searchCOs_From1Traj requests 50 orbits ranging evenly in [12,150] MeV. They are found by searchCOs_From1Traj and then saved in []workSpace/searchCO.out_COs.

(iii) Running searchCOs_From1Traj has the additional effect of creating a new input data file to zgoubi, namely, zgoubi_searchCO-Out_MATRIX.dat.
Copy that file into zgoubi.dat and run ../../zgoubiPackage/zgoubi/zgoubi. It can be checked that zgoubi.res contains the 50 matrices ("1-turn maps") corresponding to the 50 closed orbits.

(iv) Run then ../../tools/betaFromMatrix/betaFromMatrix. This will generate betaFromMatrix.out that contains optical functions for the 50 orbits.
They can be plotted using "gnuplot ../../tools/betaFromMatrix/gnuplot_betaFromMatrix.cmd (tunes can be plotted using "gnuplot ../../tools/tunesFromMatrix/gnuplot_tunesFromMatrix.cmd

(v) Results are summarized in the figures next page.

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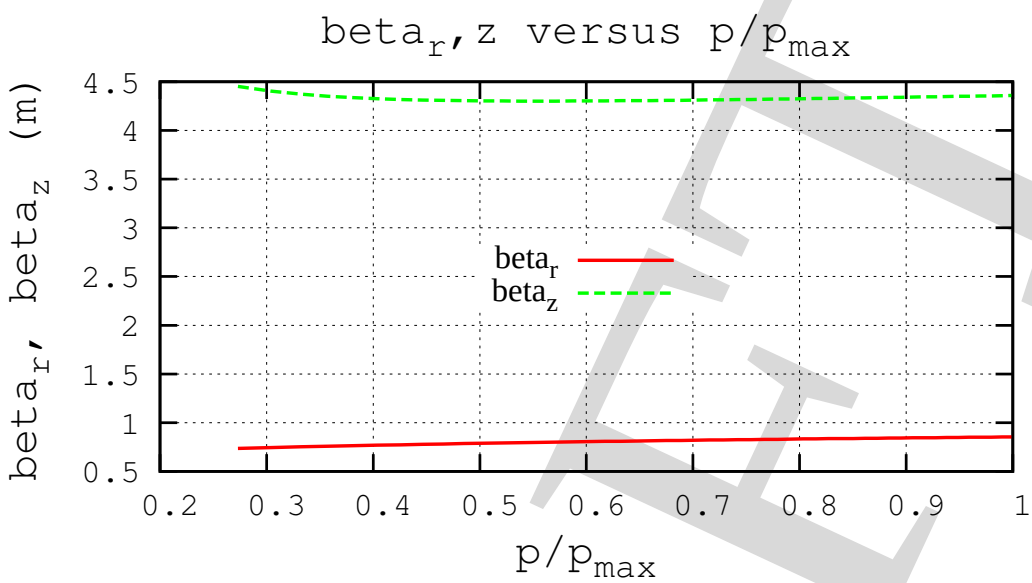
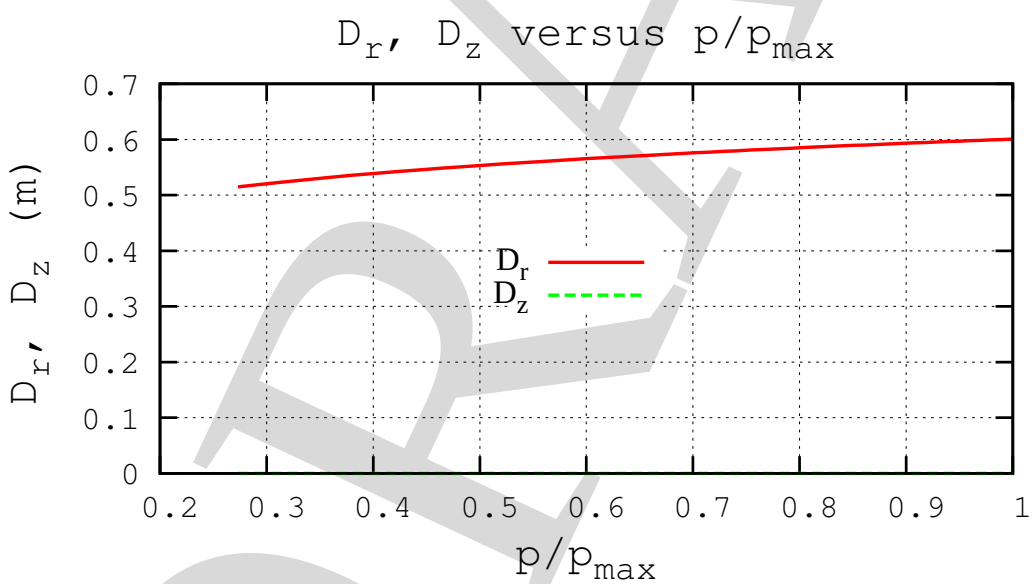


Values of the betatron functions in the middle of the drift.



Values of the dispersion functions in the middle of the drift.

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3 Propagating the beta functions

This can be achieved using zgoubi.plt file.

zgoubi.plt is filled if IL=2 in `FFAG`. The file contains particle coordinates step by step, one particle after the other.

The transport coefficients (the matrix T below) can be computed from incoming and outgoing particle coordinates, this is addressed below. Knowing T allows transporting the '"beam matrix', σ, following

$$\sigma_2 = T\,\sigma_1\,\tilde{T}, \qquad \sigma = \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix}$$

The initial beam matrix thus needed, $[T_{ij}]$, can be obtained beforehand using `MATRIX` together with `OBJET`, option KOBJ=5. What this preliminary `MATRIX` run does is, first, getting the one-turn (or one-cell) transport matrix $[T_{ij}]$ from drift center to drift center, for each plane, and next, getting the periodic optical functions $\alpha,\ \beta$ at the drift center, by identification with the "Twiss matrix",

$$\begin{pmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{pmatrix} = I\ \cos\mu + J\ \sin\mu$$

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François Méot
BNL, C-AD, Upton, NY

Ray-tracing tutorial

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EXERCISE #3

- Acceleration Cycle -

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1 Goal of the exercise

In this exercise we will gather the necessary files and simulate a complete acceleration cycle.

Recommendations

In the exercise directory, you'll find a "workFiles" directory which contains the input data files to Zgoubi for the exercise, and a "workSpace" directory.

It is stronly encouraged to leave "workFiles" untouched, and work in "workSpace" rather, using the files copied from "workFiles".

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2 RF frequency law

• The 150 MeV FFAG is a scaling lattice, the field law in both F and D dipole components of the DFD triplet satisfies

$$\frac{B}{B_0} = \left(\frac{r}{r_0}\right)^K$$

A particle will be launched with a small axial ("paraxial") motion, and on RF phase close to the synchronous phase ϕ_s.

In order to achieve the acceleration cycle from 12 to 150 MeV, the RF frequency is increased from 1.641 to 4.513 MHz. The synchronous phase $\phi_s = 20°$ and the peak voltage $\hat{V} = 10$ kV are maintained constant, thus about 10000 turns (3.10 ms) are needed. A single cavity is used in the simulations, located in the middle of one of the 12 drifts.

The RF phase $\phi(t) = 2\pi \int_0^t f_{RF}(t)dt$ upon arrival of a particle at the RF gap at time t, is computed by interpolating f_{RF} from the frequency revolution law. The latter might be derived from the scaling law, above, using the revolution time $\tau = 2\pi r/\beta c$ on an orbit with radius r at energy $E = pc/\beta$, namely

$$\tau = \tau_0 \left(\frac{p}{p_0}\right)^{\frac{-k}{k+1}} \frac{E+m}{(E_0+m)}$$

with $E + m$ the particle energy. However, it is as straightforward to compute τ numerically by prior ray-tracing of a few tens of closed orbits taken between 17 and 180 MeV. This in addition guarantees agreement with the zgoubi model (although, as seen in the table below, the formula above on the one hand and the tracking on the other hand happen to lead to extremely small difference in revolution time).

This is dealt with in the next section.

Revolution time (per cell)

Energy (MeV)	zgoubi.frequency.law μs	Theoretical formula μs
12	5.077940047287E-02	5.07794020E-02
30	3.436634182001E-02	3.4366770E-02
60	2.590415412372E-02	2.59045265E-02
90	2.215605052231E-02	2.21585577E-02
120	1.994627204981E-02	1.99443431E-02
150	1.846322221338E-02	1.84656184E-02

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3 Setting up files for acceleration

(i) Copy []/4.exercise#3_RFFrequencyLaw_acceleration/workFiles/zgoubi_searchCO-In.dat and []/4.exercise#3_RFFrequencyLaw_acceleration/workFiles/searchCO.data to []/4.exercise#3_RFFrequencyLaw_acceleration/workSpace.

(ii) Then run tutorial/tools/searchClosedOrbit/searchCOs_From1Traj. The input file searchCO.data to searchCOs_From1Traj request 50 orbits ranging evenly in [12,150] MeV. They are saved in []workSpace/searchCO.out_COs.

(iii) []4.exercise#3_RFFrequencyLaw_acceleration/workFiles contains the conversion program, Et2nf, from orbits to frequency law.

Prior to executing Et2nf, it is necessary to link (or copy) searchCO.out_COs to Et2nf.In2, in workSpace. Also, copy ../workFiles/Et2nf.In to workSpace.

After execution of Et2nf then results are saved in Et2nf.Out.

(iv) Copy (or link) Et2nf.Out to zgoubi.freqLaw.In. `CAVITE` with option 6 will take its data from the latter during acceleartion.

(v) Now the acceleration cycle can be run. The zgoubi input data necessary for that is ../workFiles/accelerationCycle.dat.

(vi) Results are summarized in the figures in the next pages.

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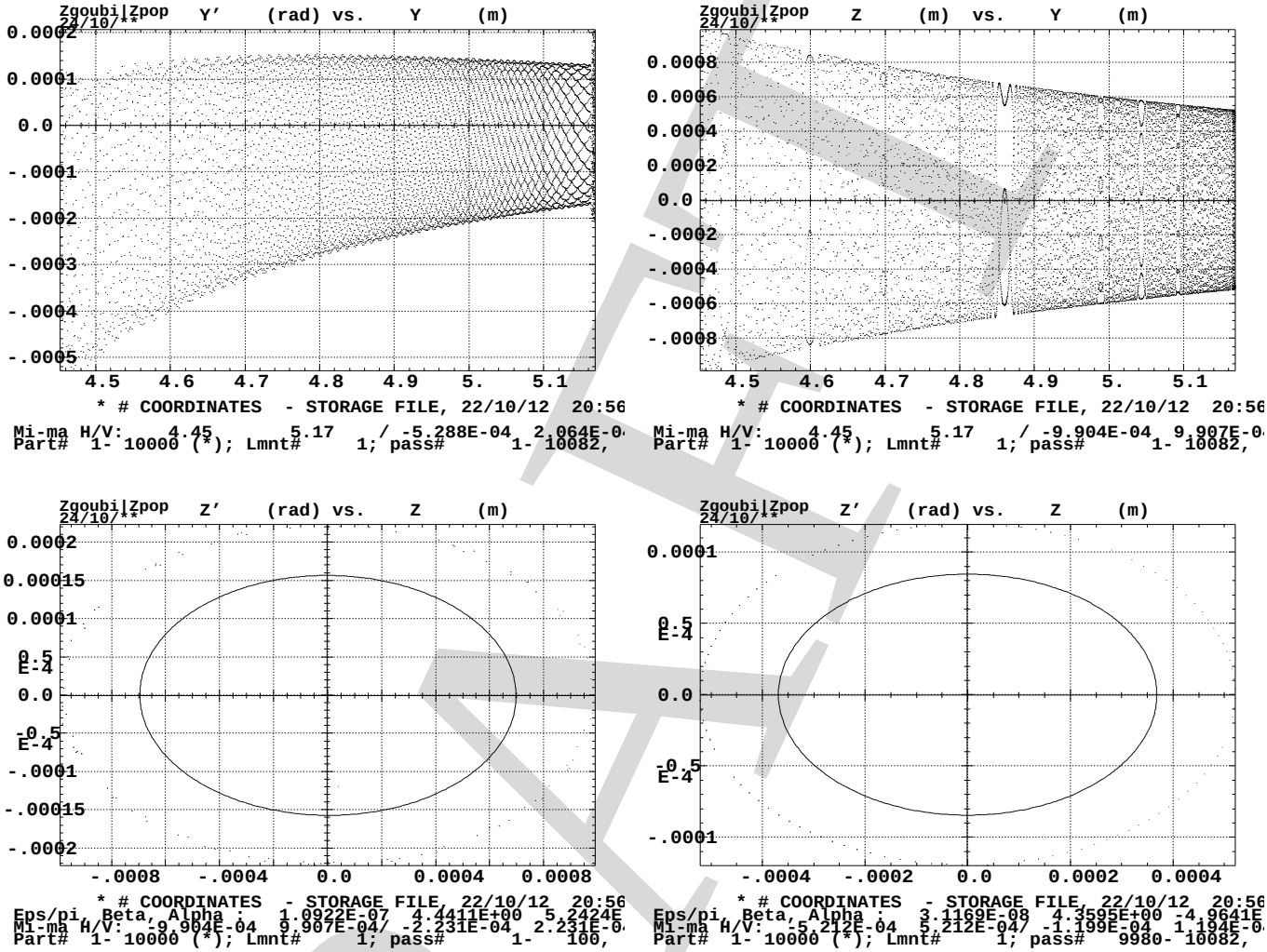

Top left : R,R' phase space : top right : Z versus radius. Bottom left : initial vertical phase space Z,Z', bottom right : final Z,Z'.

The vertical damping (bottom graphs) satisfies $p \times \epsilon_Z =$**Constant, namely, after** 10^4 **turns about,**

$$(0.988\, p_0) \times 3.1\, 10^{-8} \approx 0.306\, p_0, \qquad (0.28\, p_0) \times 1.1\, 10^{-7} \approx 0.307\, p_0$$

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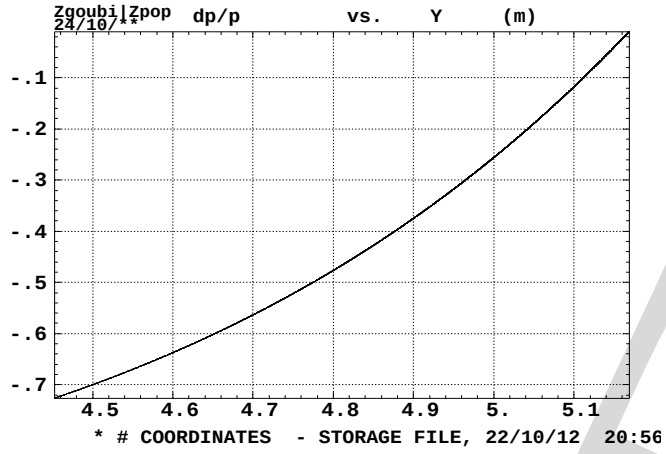
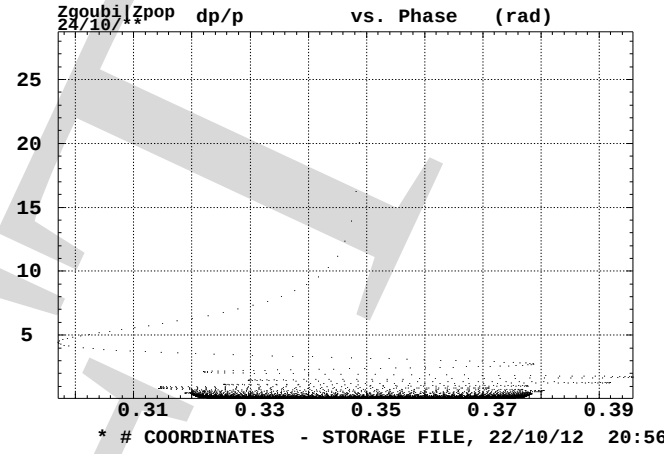
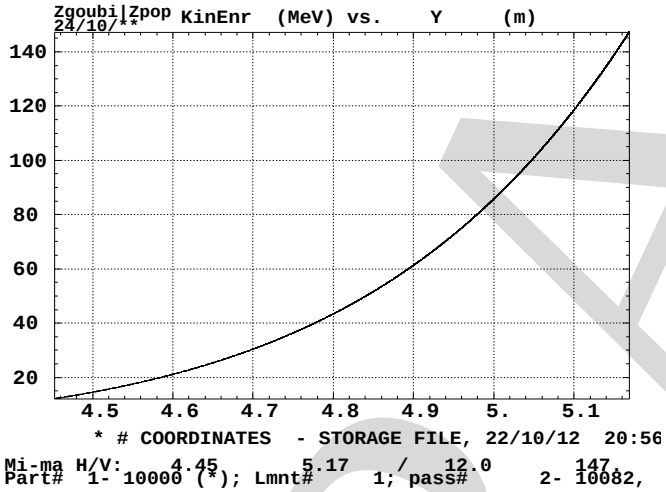

Zgoubi|Zpop
24/10/**
dp/p vs. Y (m)
-.1
-.2
-.3
-.4
-.5
-.6
-.7
4.5
4.6
4.7
4.8
4.9
5.
5.1
* # COORDINATES - STORAGE FILE, 22/10/12 20:56
Mi-ma H/V: 4.45 5.17 / -0.727 -1.014E-0
Part# 1- 10000 (*); Lmnt# 1; pass# 2- 10082,


Zgoubi|Zpop
24/10/**
dp/p vs. Phase (rad)
25
20
15
10
5
0.31
0.33
0.35
0.37
0.39
* # COORDINATES - STORAGE FILE, 22/10/12 20:56
Mi-ma H/V: 0.297 0.396 / 5.069E-02 28.7
Part# 1- 10000 (*); Lmnt# 1; pass# 1- 9000,


Zgoubi|Zpop
24/10/**
KinEnr (MeV) vs. Y (m)
140
120
100
80
60
40
20
4.5
4.6
4.7
4.8
4.9
5.
5.1
* # COORDINATES - STORAGE FILE, 22/10/12 20:56
Mi-ma H/V: 4.45 5.17 / 12.0 147.
Part# 1- 10000 (*); Lmnt# 1; pass# 2- 10082,

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