Tuesday Tutorial

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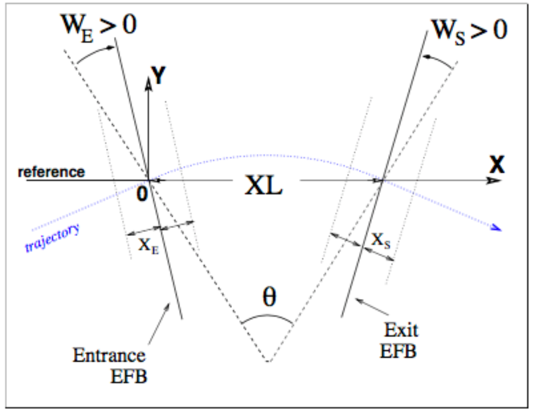
Exercise 1: Statistics of Synchrotron radiation

e- enters



Geometry and parameters of *BEND* : *XL* = length, θ = deviation, W_E, W_S are the entrance and exit wedge angles. The motion is computed in the Cartesian frame (O, X, Y, Z).

Emit photons

e- leaves

rho = 24.9 m

Electrons pass through single dipole

B = 2.406 T
XL = 2.4449 m

Input electron energy: 18 GeV

$$B\rho = 6.004 * 10^4 kG\ cm$$

Monte Carlo photon emission

Probability of emission of k photons: $$p(k) = \frac{\lambda^k}{k!}\exp(-\lambda)$$

Average number of photos per radian: $$\lambda = \frac{20er_0}{8\hbar\sqrt{3}}\beta^2 B\rho\frac{\Delta s}{\rho}$$

Critical energy $$\epsilon_c(eV) = \frac{3\gamma^3 c}{2\rho}\frac{\hbar}{e}$$

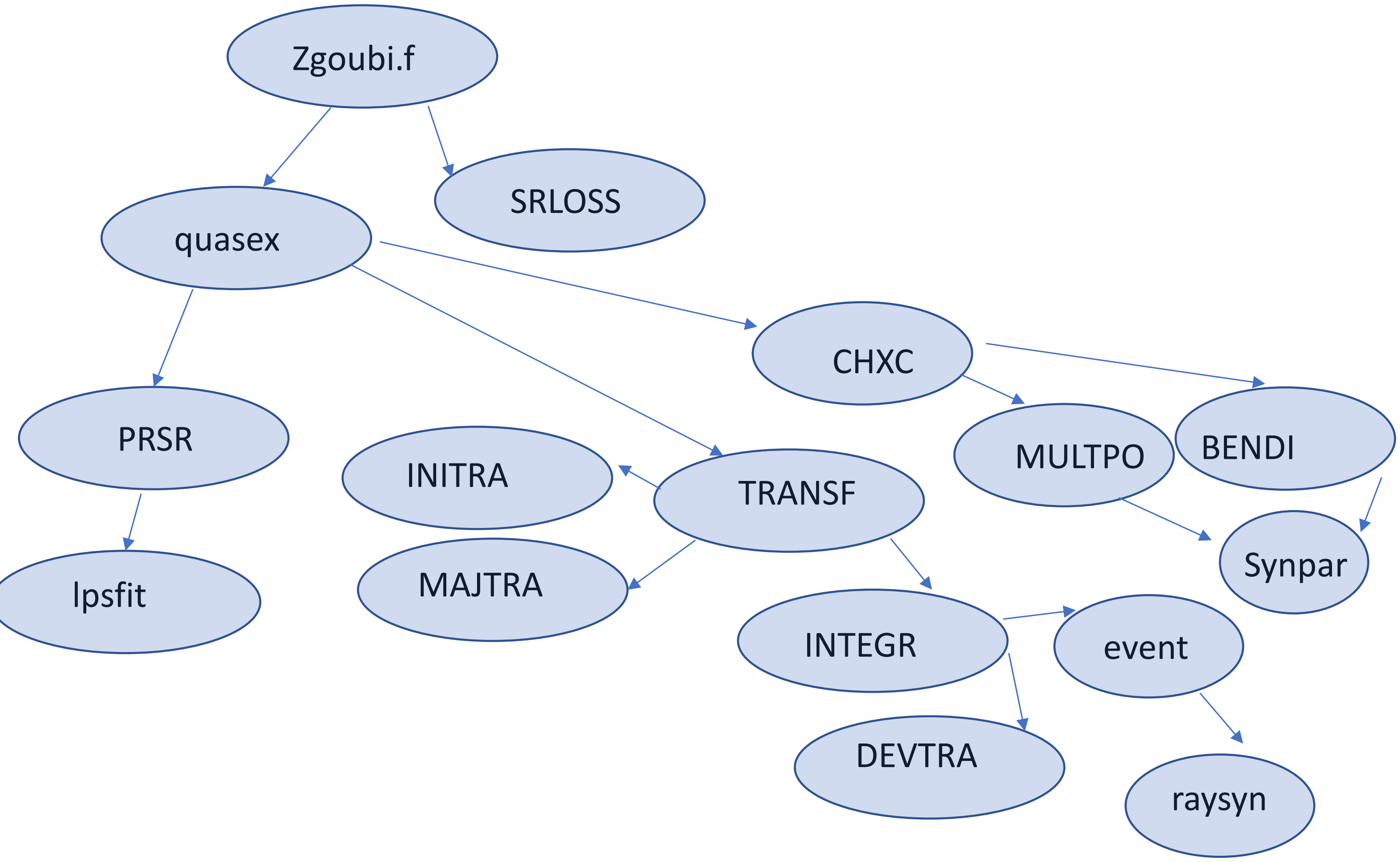
Average energy loss per particle

$$\Delta E(eV) \;=\; \frac{2}{3}r_0 c\gamma^3 B(T)\Delta\theta$$

Average Energy of photon radiation $$<\epsilon>= \frac{8}{15\sqrt{3}}\epsilon_c$$

Average number of Radiated photons per particle $$N = \Delta E / <\epsilon>$$

Code diagram



Zgoubi input file

```
!Compute Synchrotron radiation in a bend
 'MCOBJET'                                                    1
60.041537111472856d3
3
5
2 2 2 2 2 2
0. 0.  1.0e-6 0.  0. 1.  !0. 0.  0. 0.  0. 1.
0.  26.608754   0.        2
0.  11.302651   0.e-9      2
0. 1.         1e-4        2
123456 234567 345678

 'PARTICUL'                                                   2
0.511  1.602176487D-19  0. 0. 0.
 'SRLOSS'                                                     3
1
BEND
1  123456

 'BEND'                                                       4
0
2.449016210216713777e2   00.   0.4007133486721675049
0.00  000.00  0.04908738521234051935
4 .2401  1.8639  -.5572  .3904 0. 0. 0.
0.00  000.00  0.04908738521234051935
4 .2401  1.8639  -.5572  .3904 0. 0. 0.
1. cm
3 0. 0. 0.

 'END'                                                        5
```

KEYWORDS

MCOBJET: initial conditions of particles
PARTICUL: particle definition
SRLOSS: turn on/off synchrotron radiation
BEND: define dipole magnet
FAISTORE: print particle coordinates (.fai)
REBELOTE: track through lattice again
END: done!

SRLOSS keyword. (p. 287 in manual)

Example

```
'SRLOSS'
1.1
BEND
1  123456
```

Turn on SR

Set to 1.1 to allow print out to zgoubi.SRLOSS.Out

SR in dipole

Option
(1: dp only)

Random seed for monte carlo
Emission algorithm

Exercise 1 overview

Exercise 1a

Understand .res file and confirm calculations

Exercise 1b

Examine SRLOSS file and plot results in different columns

Exercise 1a

Look at DipoleSR.dat.
It contains the definition of 18 GeV electrons passing through a dipole.

The number of particles may be set in MCOBJET

Number of turns tracked may be set in REBELOTE

You may change the step size also, in the BEND element

Please look in the manual at each of these keywords to understand where to make these changes

Run the DipoleSR.dat file and examine the resulting zgoubi.res file

Output .res file contains results of Zgoubi calculation

Run Zgoubi to produce .res file
Try to verify synchrotron radiation results yourself in the jupyter notebook!
Press + button to insert new cell
(lambda has already been done for you)

- Critical energy
- Average photon energy
- average energy loss per particle

Example Expected Zgoubi.res file:

```
Length    =  2.449016E+02 cm
Arc length   =  2.450000E+02 cm
Deviation   =  5.625000E+00 deg.,    9.817477E-02 rad
GAP   =  0.000000E+00 cm
Gradient   =  0.000000E+00 kG/cm
Grad-prime   =  0.000000E+00 kG/cm^2

Field  =  2.4059445E+01  kG   (i.e.,   4.0071335E-01 * SCAL)
Reference curvature radius (Brho/B) =   2.4955495E+03 cm
Skew  angle  =  0.000000E+00  rad

Entrance  face
DX =      0.000    LAMBDA =      0.000
Wedge  angle  =  0.049087 RD

Exit     face
DX =      0.000    LAMBDA =      0.000
Wedge  angle  =  0.049087 RD
```

```
 ***  Warning : entrance sharp edge entails vertical wedge focusing approximated with first order kick, FINT values entr/exit :    0.000

 ***  Warning : exit sharp edge entails vertical wedge focusing approximated with first order kick, FINT values entr/exit :    0.000

  * Theoretical S.R. parameters in local *dipole* field :
   Bending radius (Brho/B) :   24.955495    m,   deviation angle :  9.81747704E-02 rad
   Average energy loss per particle : Eloss = (2/3).r0.c.gamma^3.B.Ang/1000     5814.3427     keV
                   (elctrn with bta~1 : 88.463*E[GeV]^4/rho[m]*(Ang/2pi))
   Critical photon energy : Ec = 3.gamma^3.c/(2.rho)*(Hbar/e)/1000 =          518.40209     keV
   Average photon energy : <Eph> = 8/(15.sqrt(3)) *Ec =                     159.62645     keV
   rms photon energy : Eph_rms = 0.6383.Ec =                               330.89605     keV
   Number of average photons per particle inside dipole : N = Eloss/<Eph> =     36.424683

  * Theoretical S.R. parameters, summed over magnets up to this point :
   Average energy loss :                                          5814.3427     keV/particle
          - relative to initial energy :                          3.23019038E-04
   Number of average photons :                                       36.424683     /particle

            Field has been * by scaling factor    60.041537

   KPOS =  3 :  automatic positioning of element,
     XCE, YCE, ALE =   0.000000000      0.000000000     -4.9087385212E-02 cm/cm/rad

            Integration step :   3.000     cm

 A    1  1.0000     0.000     0.000     0.000     0.000        244.902    -0.002    -0.049     0.000     0.000          1

   KPOS =  3.  Automatic  positionning  of  element.
      X =   0.000     CM    Y =   0.000     cm,  tilt  angle = -4.908739E-02 RAD


 Cumulative length of optical axis =    2.45000000     m ;  Time  (for ref. rigidity & particle) =   8.172320E-09 s
```

Exercise 1b

Edit DipoleSR.dat
to change number of particles, (up to ~3000)
and number of turns (up to ~100) and
step size and SRLOSS random seed

Examine zgoubi.SRLOSS.out after each change and running zgoubi.

Using the zgoubi.SRLOSS.out file

40 columns, note that python indexes from 0, so 0…39

Python read command with some useful columns:

```
turn,emit,xpm,dE,sigE,theo_dEav,Eav_phot,Erms_phot=np.loadtxt('%s/%s'%(FL,'zgoubi_3000p_s123456_ss1cm.SRLOSS.Out'),skiprows=5,usecols=(4,27,31,35,36,37,38,39),unpack=True)
```

Turn: turn number. (col. 4)
Emit: longitudinal emittance (KeV-cm). (double check…). (col. 27)
xpm: total momentum (KeV/c). (col. 31)
dE: fluctuation of average bunch energy (MeV). (col. 35)
sigE: local contribution to energy spread . (col 36)
Theo_dEav: theretical energy loss per particle. (col. 37)
Eav_phot: average energy of a radiated photon. (col 38)
Erms_phot: RMS photon energy. (col 39)

See Exercise 1 Jupyter file for further plotting tools

Exercise 2 overview

Exercise 2a

Calculate the linear parameters in the ESRF lattice and also how to plot twiss functions around the ring

Exercise 2b

Understand how to include twiss zgoubi file into another zougbi file to use for tracking. Examine CAVITE settings and track several sets of initial conditions and observe evolution to equilibrium

Exercise 2a:

We work with the file ESRF_18GeV_Twiss.inc. It is set up to calculate twiss parameters.

```
 'OBJET'
1
60.041537111472856d3
5
.001 .01  .001 .01  .0 .0001
.0 .0 .0 .0 .0 1.

 'SRLOSS'
6
0
BEND
1  123456

'PARTICUL'                                    An electron
5
0.511  1.602176487D-19  0. 0. 0.
```

We continue with the file ESRF_18GeV_Twiss.inc.

'MARKER'   ringstart   (MARKER is used to allow this lattice file to be included into a file for tracking)

'MARKER' ringend

```
!'CAVITE'
! 2      .1          .1 is to fill zgoubi.cavite for plot using zpop/7/20
! 812.80224   300                          orbit length, h
! 0.7443266709d9  2.6179938779914943655           volts, phi_s rad

  'TWISS'
 2   1.   1.   PRINT
```

(Note that the 'CAVITE' must be commented out for twiss calculation)

Run ZGOUBI to obtain the twiss functions around the ring:

zgoubi –in ESRF_18GeV_Twiss.inc

This should produce the file zgoubi.TWISS.out . Use Exercise 2a notebook to plot the results. Global lattice parameters, such as tunes and chromaticities, are also available in zgoubi.res file.

Exercise 2b:

We work with the file ESRF_18GeV.dat. This file gets all the lattice elements from another file named ESRF_18GeV_Twiss.inc using ”INCLUDE” keyword.

```
 'MCOBJET'
60.041537111472856d3
3
100
2 2 2 2 2 2
0. 0.  0. 0.  0. 1.
0.  26.608754   0.        2
0.  11.302651   0.e-9      2
0. 1.        1e-4        2
123456 234567 345678
```

Use phase space ellipse

# of particles

Hor. Ver. And long. Twiss parameters (alpha, beta and epsilon) for generating Gaussian distribution

Random seeds to generate distributions

```
 'SCALING'
1 3
QUADRUPO
2
60.041537111472856 60.041537111472856
1  999999
BEND
2
60.041537111472856 60.041537111472856
1  999999
SEXTUPOL
2
60.041537111472856 60.041537111472856
1  999999
 'FAISCEAU'
 'FAISTORE'
zgoubi.fai
1
```

Scaling multiplies field values by constant. These are set for 18 GeV, but could be changed if different energy is required. We do not accelerate here so the initial and final values are the same.

```
 'PARTICUL'
0.511  1.602176487D-19  0. 0. 0.
 'SRLOSS'
1
BEND
1  123456

 'OPTIONS'
1 1
WRITE ON

'INCLUDE'
1
ESRF_18GeV_Twiss.inc[ringstart:ringend]

'CAVITE'
2
812.80224   300
0.7443266709d9  2.617993877991494365

'OPTIONS'
  1   1
  WRITE ON
'REBELOTE'
200  0.1  99
'FAISCEAU'
'END'
```

Synchrotron radiation is on

Include the lattice elements from the twiss file

Note that we did not include ‘CAVITE’ in the twiss file. It is included here to compensate the synchrotron radiation and provide longitudinal focusing.

orbit length, h

volts, phi_s rad

Option2 follows dE=qVsin(phi_s)

Track 200 turns

Exercise 2b (Tracking)

Run: zgoubi –in ESRF_18GeV.dat

This is 100 particles running up to 200 turns and watch evolution to equilibrium. Compare the calculated rms value with simulation results. Calculated values can be found in the paper "JINST_008T".

Compute the synchrotron tune using the following formula:

$$\nu_s = \sqrt{\frac{heV_{rf}\eta\cos(\phi_s)}{2\pi\beta^2 E_0}}$$

Here η is phase slip factor, which is well approximated by the momentum compaction factor $\alpha = 0.3e-3$ that is found in the header of zgoubi.TWISS.out file. Compare synchrotron tune and damping time with simulation results.

Exercise 3 overview

Exercise 3a

Calculate the linear parameters in the JLEIC electron collider ring lattice and plot twiss functions around the ring. Global parameters also can be found in .res file. Note that SRLOSS and CAVITE are turned off.

Exercise 3b

Watch spin components at the different positions around the ring. Observe how the spin rotates across the spin rotator. Note again SRLOSS and CAVITE are off. Introduce vertical misalignments of quadrupoles, using FIT routine to find invariant spin field on the closed orbit.

Exercise 3c

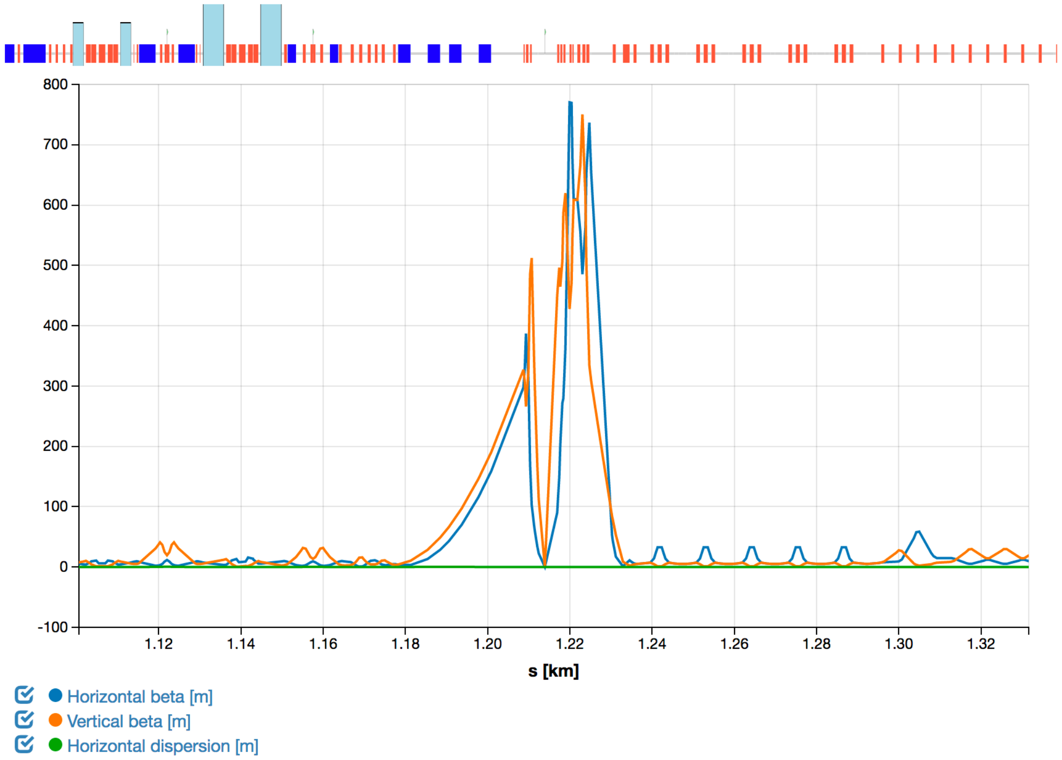
Turn on SRLOSS and include CAVITE, adjusting spin tune using zero length spin rotator “SPINR” to be away from the zero integer resonance by 0.01. Perform one particle spin tracking with initial spin conditions aligned along the invariant spin field direction. Track for several hundred turns and observe spin dynamics. Now further adjust spin tune to be on the synchrotron tune ~0.027. Track single particle again and observe spin dynamics.

Exercise 3a:

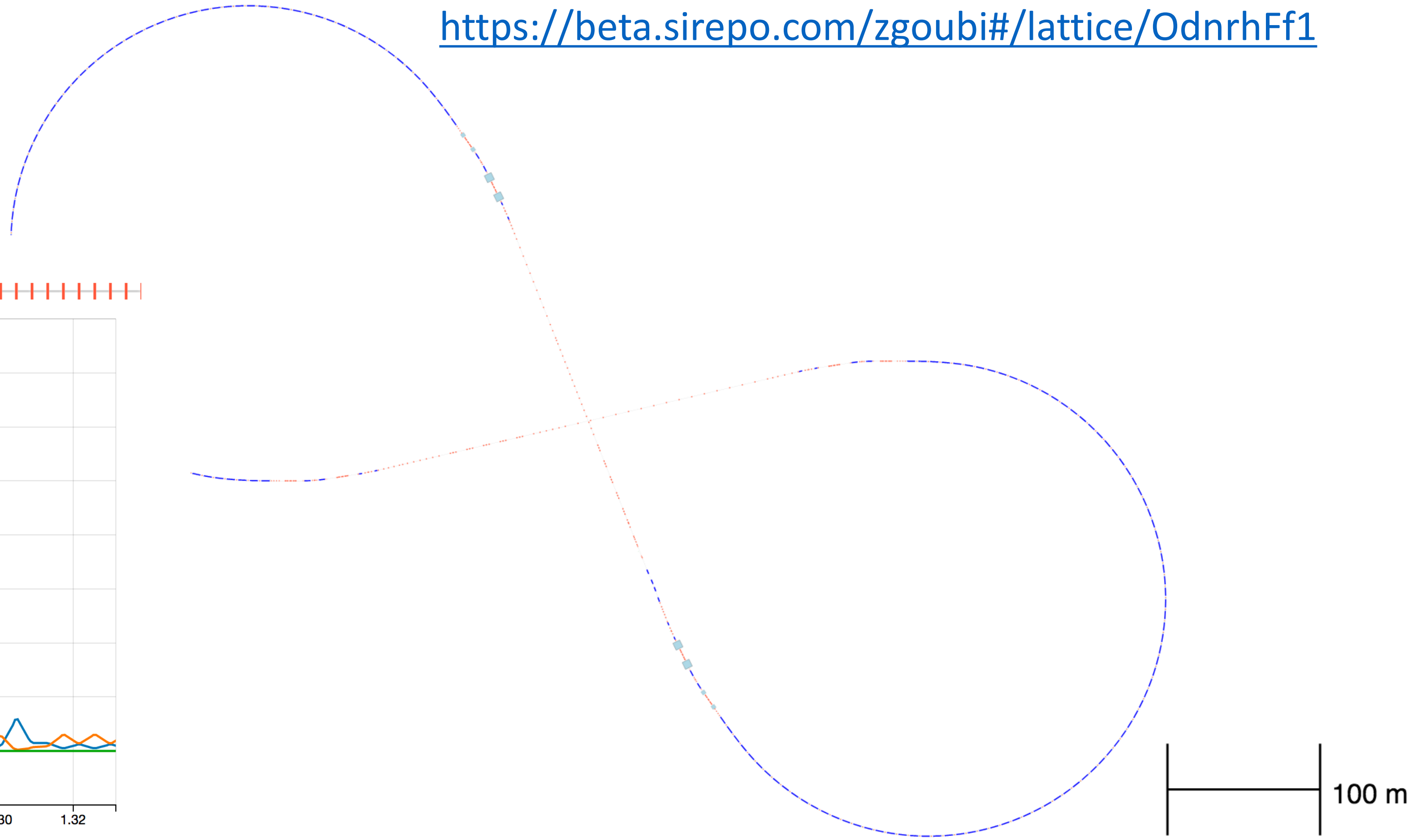
Run: zgoubi –in jleic_bare_twiss.inc

Use Exercise 3a jupyter notebook to obtain lattice functions and global parameters, such as tunes and chromaticities, in zgoubi.TWISS.Out.

Geometry and Twiss functions from Sirepo



https://beta.sirepo.com/zgoubi#/lattice/OdnrhFf1



Exercise 3b:

Run: zgoubi –in jleic_bare_spin_include.dat

(This .dat file includes jleic_bare_twiss.inc, which we just used for twiss calculations, except that we just track one single particle one time around the ring.)

Use Exercise 3b jupyter notebook to observe spin rotation.

Next we use "FIT" to find the invariant spin direction after introducing vertical quadrupole misalignments

```
'SPNTRK'
  4
  0. 0. 1.
```

```
'FIT'
3  save spinFITVals.save
4  10 0 [-1.,1.]
4  11 0 [-1.,1.]
4  12 0 [-1.001,1.001]
4    1e-10
10.1 1 1 #End 0 1. 0
10.1 1 2 #End 0 1. 0
10.1 1 3 #End 0 1. 0
10   1 4 #End 1. .2 0
```

Exercise 3b: continued

Run zgoubi –in jleic_vma_FIT.dat

You will get zgoubi.FIT.out.dat, a new copy of the lattice but with the results of invariant spin field set as the initial spin direction

```
'SPNTRK'
4
 -1.15226337E-02  1.80246914E-02  9.99780302E-01
```

Exercise 3b: continued

Modify zgoubi.FIT.out.dat file to zgoubi.FITout.dat file

```
 'SRLOSS'
1   !  .srloss
BEND
1   123456

 'CAVITE'
2
2185.536268  1816
6759397.37376  3.02085955961


 'REBELOTE'
10000  0.4 99
```

Exercise 3c:

Run: zgoubi –in zgoubi.FITout.dat with SPINR (p.284 in the manual) set to two different values

```
 'SPINR'   SOLE     ST1
1
0  9.72
```

Spin procession angle around the axis:
9.72 degrees produces spin tune of 0.027
3.64 degrees produces spin tune of 0.01

Angle (in (X,Y) plane) between the X-axis and the spin precession axis

Use Exercise 3c jupyter notebook to observe spin dynamics.

Thank You !