Beam Dynamics with MAD - Part 3

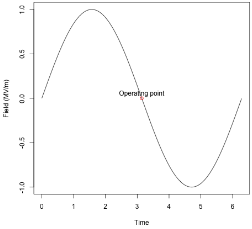
Roger Barlow

Time and Energy

1. Synchrotron oscillations
2. The RFCAVITY
3. Small oscillations
4. Large oscillations and the seperatrix
5. Acceleration

Synchrotron oscillations in a storage ring

Particles don't all have the same energy. (Small) Gaussian spread. .
Reminder (lecture 2 slide 7): Higher energy particles take longer to complete an orbit (above the transition energy, which is usually the case).
So the time distribution of the bunch gets spread out indefinitely.
To fix this, use an RF cavity with an oscillating electric field.



On-time particles: no effect
Late particles: negative kick, E reduced.
Early particles: positive kick, E increased

RFCAVITY

another MAD component

Example:
RFC1 : RFCAVITY,L=1,AT=3,VOLT=1,HARMON=1,LAG=0;

L and AT as usual
VOLT is the peak energy (units are MV)
HARMON is the harmonic: ratio of RF frequency to orbital frequency f_0 (which MAD computes)
LAG is the phase difference, in multiples of 2π
The effect of the cavity on a particle traversing at time t is

$$\Delta_E = \mathrm{VOLT} \times sin(2\pi(\mathrm{LAG} - \mathrm{HARMON} f_0 t)).$$

Assumption: transit time short compared to RF period

Particle time/energy behaviour for small deviations

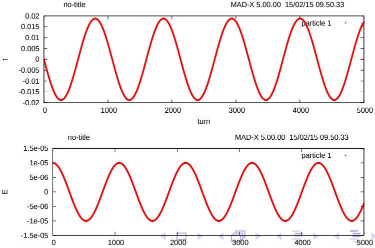
Using TRACK and, possibly, PLOT

```
RF: RFCAVITY,VOLT=1,LAG=1.5,harmon=1,L=0.1,AT=0.1;
TRACK,file=track,dump;
START,T=0.,PT=0.00001;
RUN,TURNS=5000;
ENDTRACK;
plot,table=track,particle=1,file="track1",haxis=TURN,vaxis=T,colour=1000;
```

T and PT are time and energy. PT is $\Delta E/p_0 c$

T is c times minus t w.r.t. reference (early particles have $T > 0$)

Synchrotron oscillations
Turn by turn changes **are** small
These are successions of points,
not smooth curves



Aside: using R graphics instead of PLOT

Whatever you find easiest - depends on platform etc

The data is written in files track.obs0001.p0001 etc in a format like:

```
@ NAME %19s "TRACK.OBS0001.P0001"
@ TYPE %08s "TRACKOBS"
@ TITLE %08s "no-title"
@ ORIGIN %20s "MAD-X 5.00.00 Darwin"
@ DATE %08s "15/02/15"
@ TIME %08s "10.08.12"
* NUMBER TURN X PX Y PY T PT S E
$ %d %d %le %le %le %le %le %le %le %le
1 0 0 0 0 0 0 1e-05 0 20
1 1 4.529377462e-05 6.443354482e-06 0 0 -9.853564009e-05 1e-05 0 20
1 2 1.546297318e-05 -4.871247007e-06 0 0 -0.0002290953049 9.999690441e-06 0 20
```

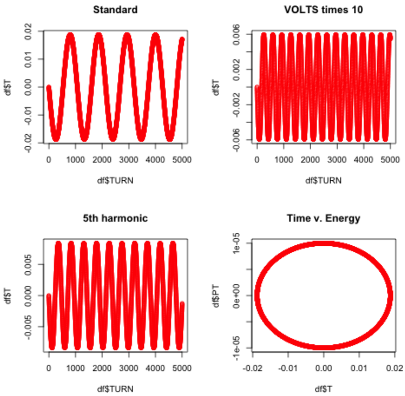
Read in R by:

```
f="your directory/track.obs0001.p0001" # or whatever
titles <- read.table(f,skip=6,nrows=1,colClasses="character")
df <- read.table(f,skip=8,col.names=titles[2:11])
plot(df$TURN,df$T,col='red') # and so on
```

Changing RF parameters

Using R graphics - not that that matters

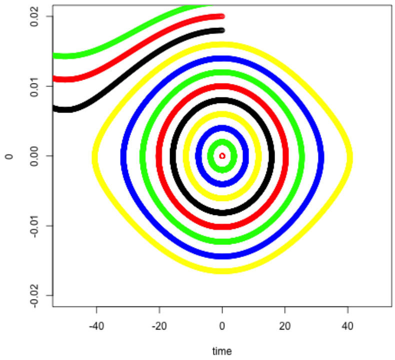
See effect of:
Increasing voltage - faster oscillation
Increasing harmonic - also faster oscillation
Particle's time and energy move around an ellipse



Larger displacements in energy and time

Generated by

```
TRACK,file=track,dump;
n=1;
while(n<13) {START,T=0,PT=(N-1)*0.002; n=n+1;}
RUN,TURNS=2000;
ENDTRACK;
```

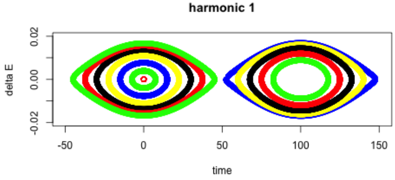


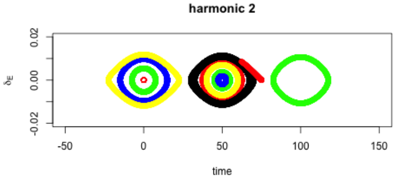
As energy offset increases:
Ellipses - linear region, SHM
Distorted ellipses - nonlinear region bounded by *seperatrix*
Outside: particles lost from time structure

Generated by

```
TRACK,file=track,dump;
n=1;
while(n<13) START,T=7.5*(N-1),PT=0; n=n+1;
RUN,TURNS=2000;

ENDTRACK;
```

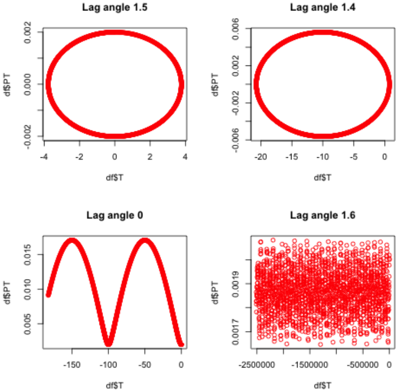




As time offset increases:
Ellipses - SHM
Distorted ellipses - nonlinear region
Particles lost from bucket but confined to adjacent ones
Bucket size depends on harmonic number

The lag angle in RFCAVITY

Value matters:
Phase difference between RF and bunch
Equivalent to offset in T
Depends on cavity position in ring
Do not rely on default of zero!
Corresponds to real technical challenge -
Ensuring cavity or cavities are in phase with beam using 'low level RF'



Acceleration

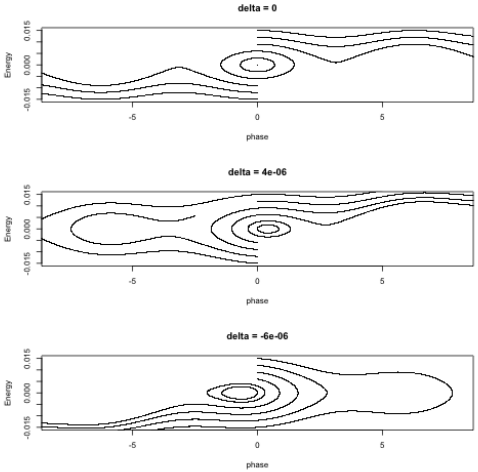
Not really done in MAD, but this is how it works...

Nominal E increases as magnets ramp up. Given particle E as fraction of nominal E falls turn by turn.

Show using R code snippet

```
e=seq(-.015,.015,.003)
t=rep(0,length(e))
for(i in 1:5000){
t=t+alpha*e
e=e+kick*sin(t+PI)+delta
points(t,e,pch='.')  }
```

Stabiity region smaller but still there. Central phase shifts. Particle energy oscillates about increasing nominal E.



Assignment

Simulate a 100 GeV electron storage ring with the same circumference as before, but at least 42 bending magnets. Run TWISS to show that the focussing is stable

Insert one RF cavity, with a peak voltage of 10 MV. Adjust the phase angle to achieve stable synchrotron oscillations. Demonstrate this with one or more plots. At what value of `PT` is stability lost?

What is the frequency you simulate for the small oscillations? Derive and evaluate this frequency from the SHM model. Do they agree?

Check by repeating this at a different harmonic number.