PyHEADTAIL examples

All our thanks to
D. Amorim, Kevin Li and Michael Schenck
CERN BE/ABP-HSC

and

Martial Fol (AZIMUTEC), Marie Gauthier and Coline Morin (ESI)

Reference: http://kli.web.cern.ch/kli/

Agenda

- Goals
- Plan
- Introduction to PyHEADTAIL
- Structure of ipython files
- Tracking examples
- Setting up the environment
  - Virtual box
  - Ubuntu
  - Anaconda
  - PyHEADTAIL

Goals

- Run macroparticle simulations with a state-of-the-art open source tracking code (PyHEADTAIL)
- Simulate several case-studies related to the course
- Play with beam parameters and observe the impact on the longitudinal beam dynamics

Plan

- 1h15 towards the end of the course in the computer room
- A virtual box with examples is prepared in the computer room
- Following popular demand, it is also possible to set up your own simulation environment on your own PC.
- The detailed procedure and examples are on the Indico site.
- Note: we should expect incompatibilities linked to open source codes!

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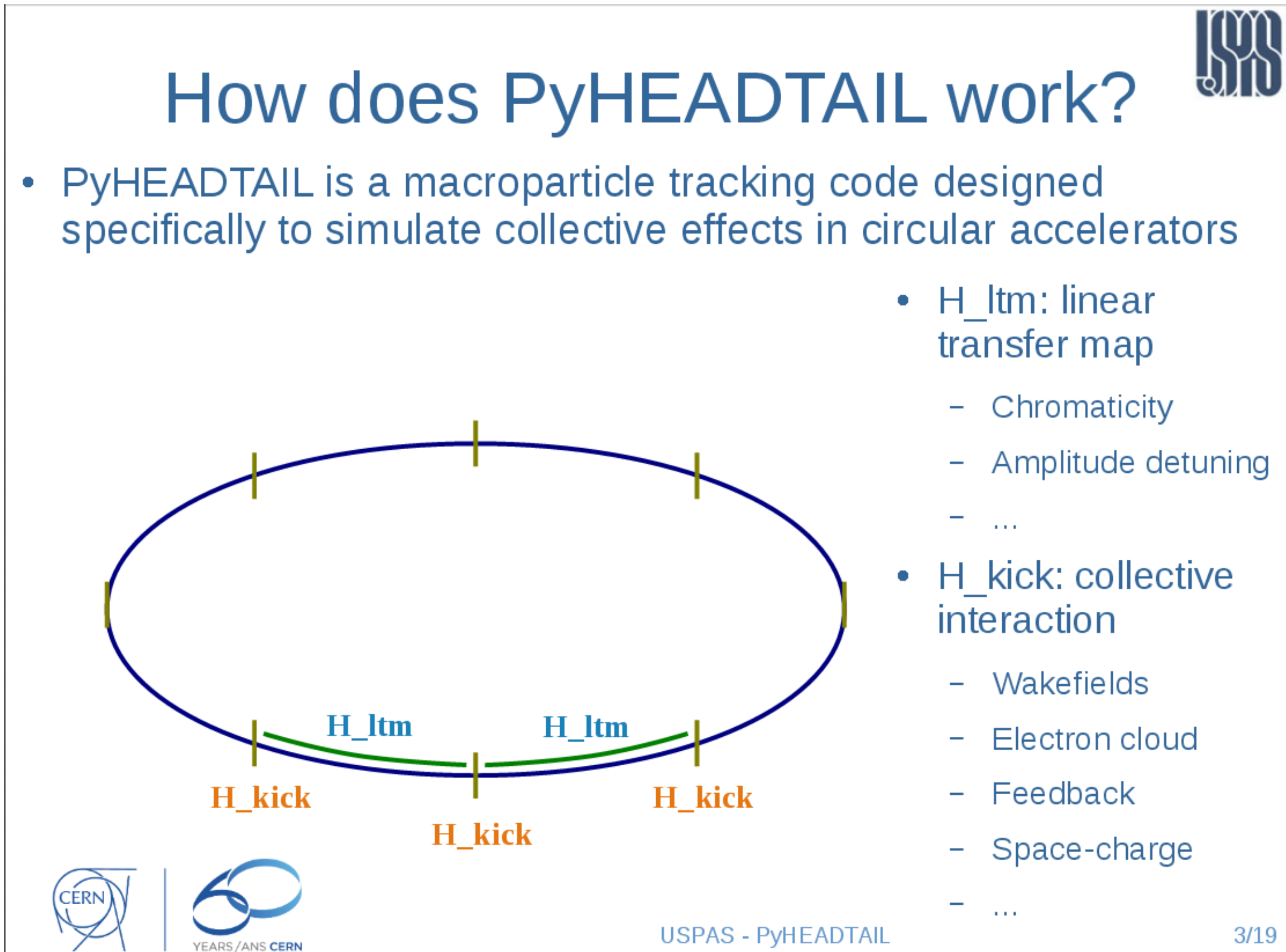
Introduction to PyHEADTAIL

- Open source macroparticle tracking code developed at CERN:
- Download link: https://github.com/PyCOMPLETE/PyHEADTAIL
- Primary use: tracking simulation of collective effects in synchrotron accelerators
  - Transverse and longitudinal beam dynamics (with feedback)
  - Electron/ion cloud
  - Impedances
  - Space charge
- Reference:
  Introduction to PyHEADTAIL: USPAS course by Kevin Li et al (2015)

- Not the only code of his kind!
  - BLOND: longitudinal dynamics simulation code https://blond.web.cern.ch/
  - HEADTAIL: the father of PyHEADTAIL! G. Rumolo et al (reference)
  - elegant: 6D tracking code developed at Argonne National Lab (link)
  - mbtrack and sbtrack: R. Nagaoka et al "Studies of Collective Effects in SOLEIL and DIAMOND Using the Multiparticle Tracking Codes sbtrack and mbtrack", PAC09, Vancouver, May 2009.
  - ORBIT (http://web.ornl.gov/~jzh/JHolmes/ORBIT.html), pyORBIT (http://sourceforge.net/projects/py-orbit/)
  - And so many others!

introduction to PyHEADTAIL

Courtesy Kevin Li
USPAS 2015



introduction to PyHEADTAIL

A real world example

Courtesy
Kevin Li
USPAS 2015

- Load Python packages and modules

```python
from __future__ import division
import cProfile, itertools, sys, time, timeit

from scipy.constants import c, e, m_p

from cobra_functions import stats, random
from beams.beams import *
from monitors.monitors import *
from spacecharge.spacecharge import *
from trackers.transverse_tracker import *
from trackers.longitudinal_tracker import *

```

A real world example

Courtesy
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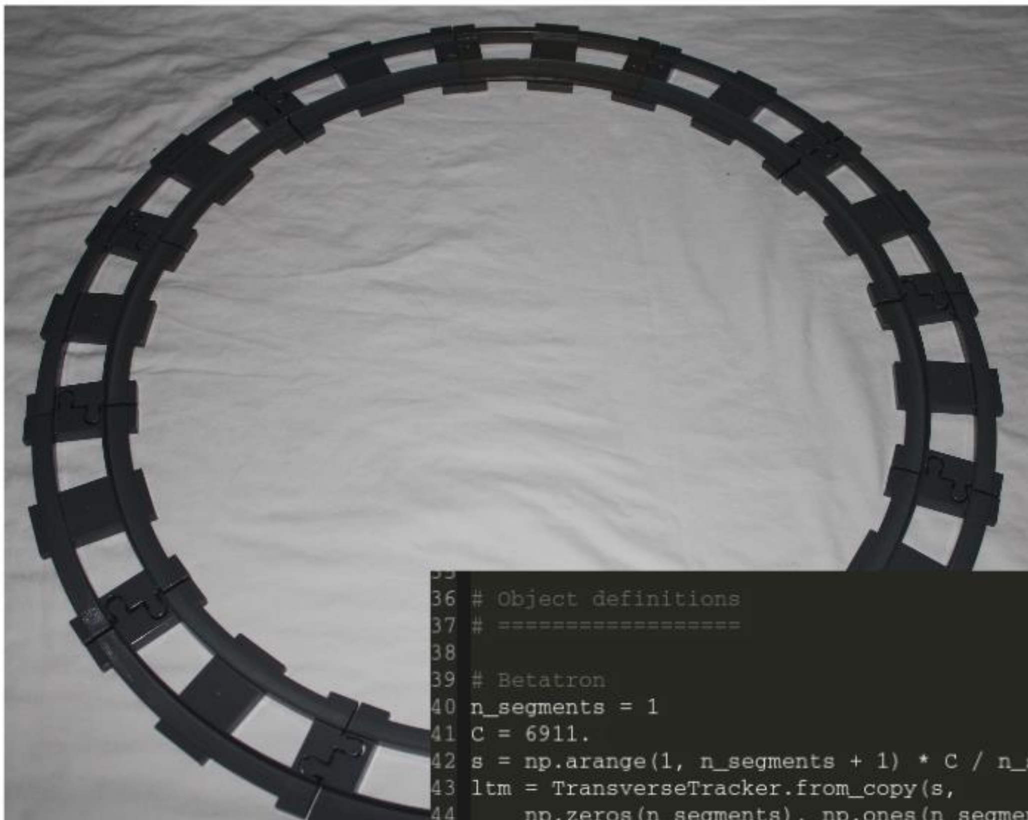
USPAS 2015



```
# Object definitions
# =================

# Betatron
n_segments = 1
C = 6911.
s = np.arange(1, n_segments + 1) * C / n_segments
ltm = TransverseTracker.from_copy(s,
    np.zeros(n_segments), np.ones(n_segments) * beta_x, np.zeros(n_segments),
    np.zeros(n_segments), np.ones(n_segments) * beta_y, np.zeros(n_segments),
    Qx, 0, 0, Qy, 0, 0)
```

- Load Python packages and modules
- Build linear periodic transfer maps

introduction to PyHEADTAIL

A real world example

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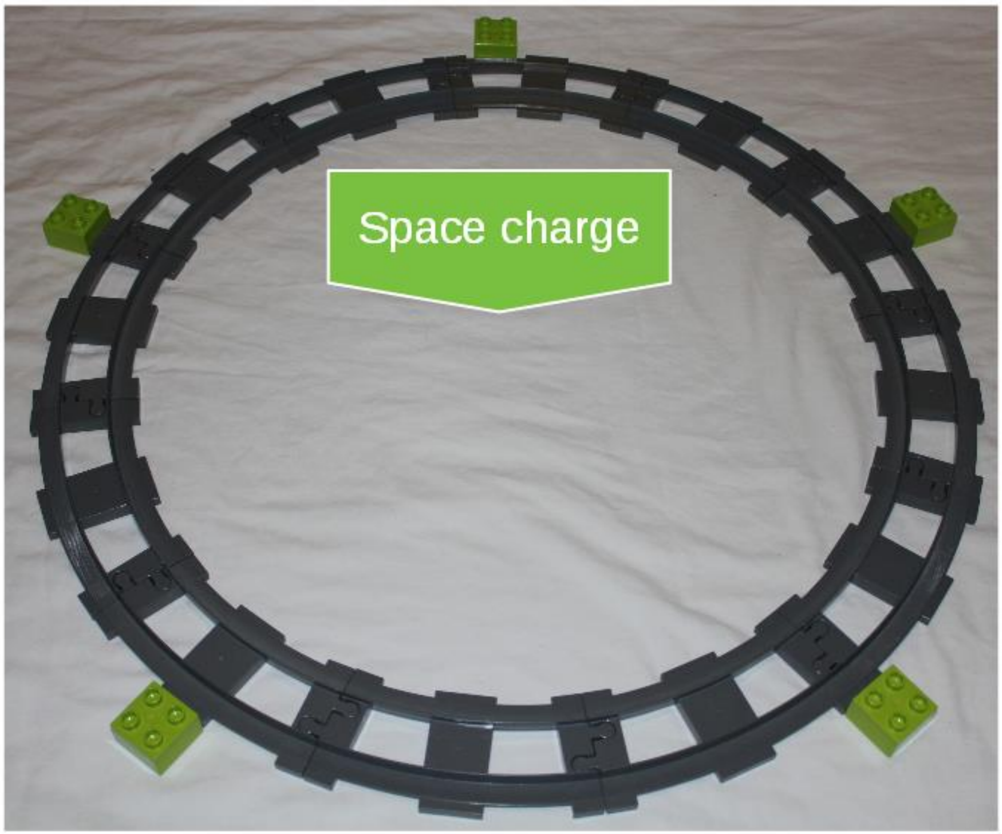
USPAS 2015



- Load Python packages and modules
- Build linear periodic transfer maps
- Add (collective) kick elements

introduction to PyHEADTAIL

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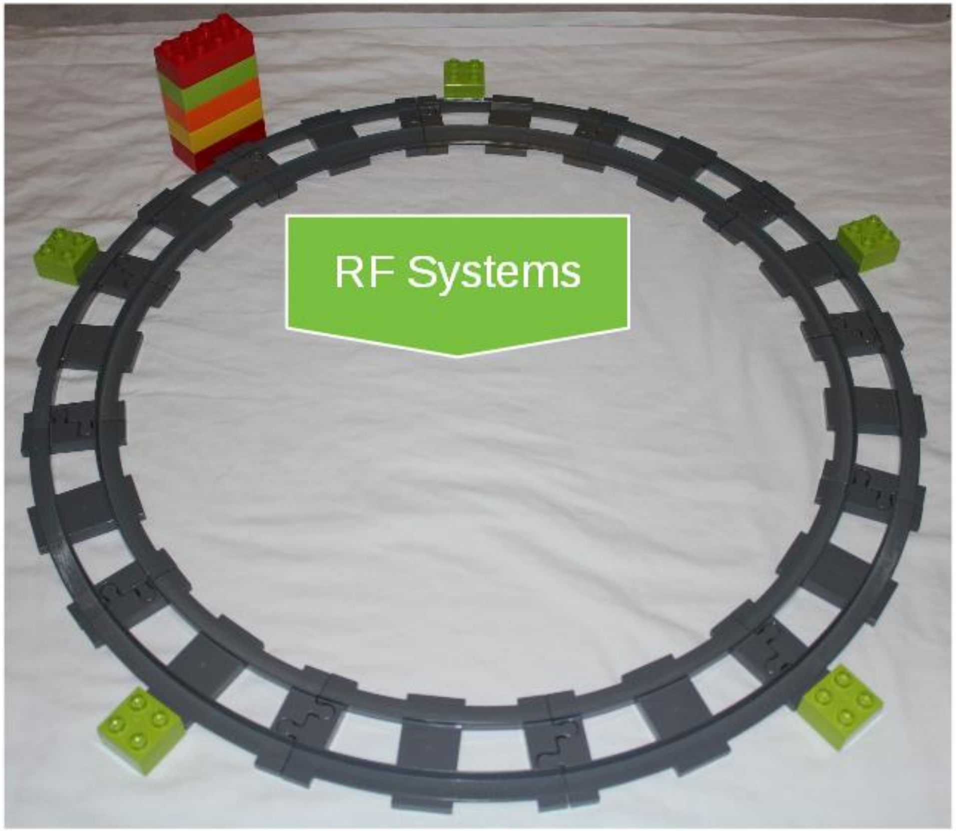

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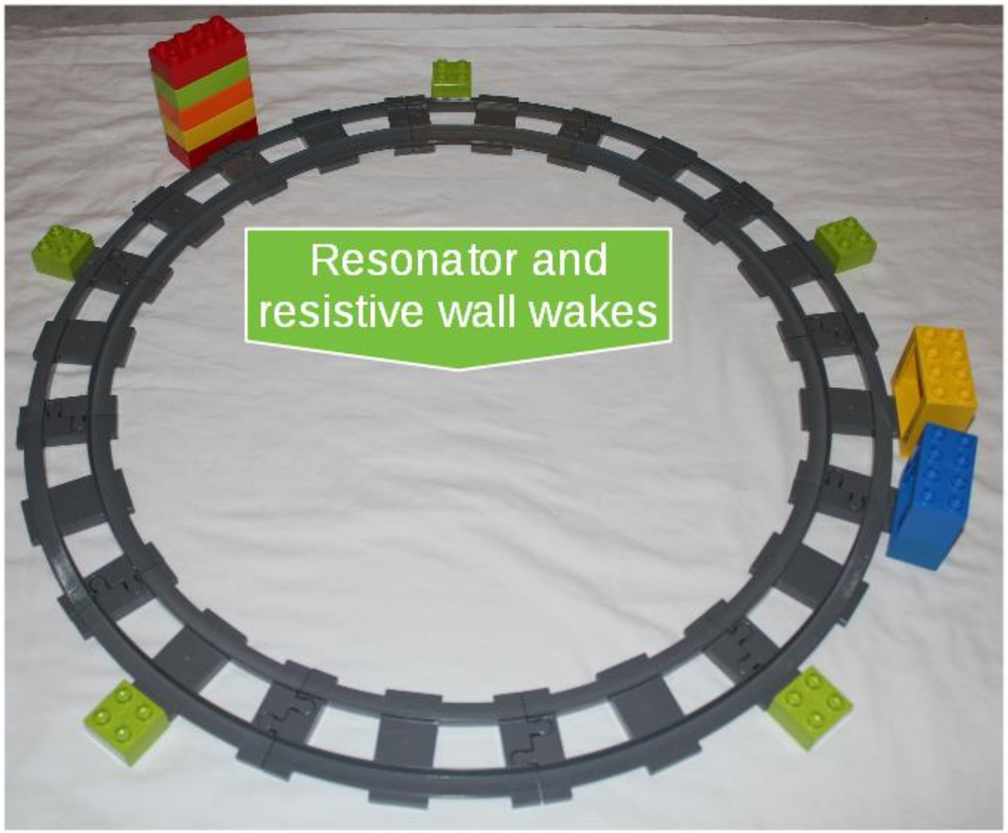

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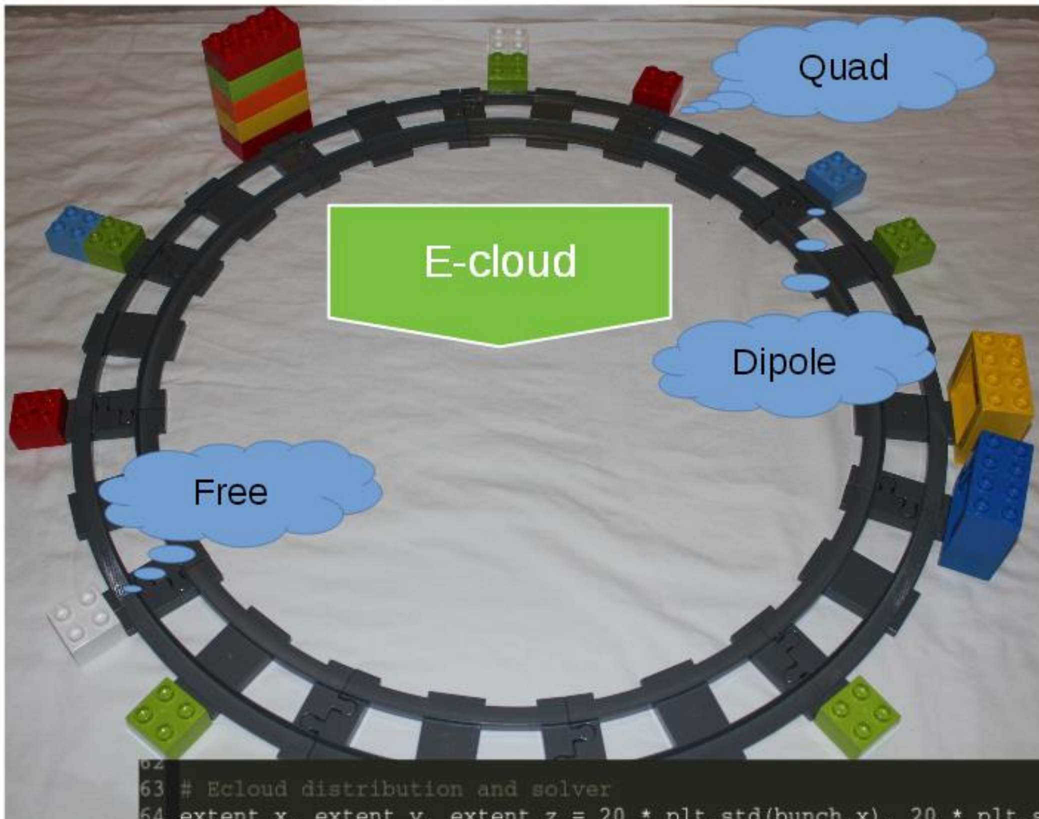
A real world example



- Load Python packages and modules
- Build linear periodic transfer maps
- Add (collective) kick elements

```
# Ecloud distribution and solver
extent_x, extent_y, extent_z = 20 * plt.std(bunch.x), 20 * plt.std(bunch.y), C / n_segments
cloud = Cloud(100000, 1e11, extent_x, extent_y, extent_z)
ecloud = SpaceCharge(cloud, 'cloud', extent_x, extent_y, 128, 128, slices)
```

introduction to PyHEADTAIL

A real world example

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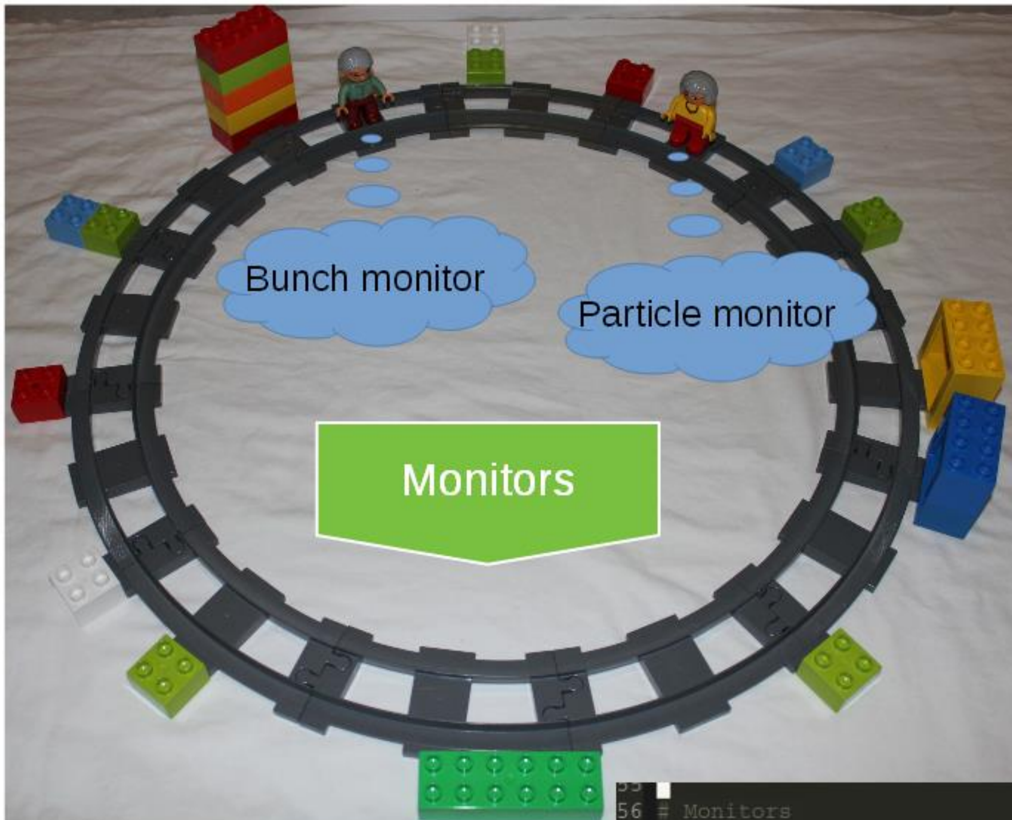
USPAS 2015



- Load Python packages and modules
- Build linear periodic transfer maps
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```
# Monitors
bunchmonitor = BunchMonitor('bunch', n_turns, slices)
particlemonitor = ParticleMonitor('particles', n_turns, slices)
```

introduction to PyHEADTAIL

A real world example

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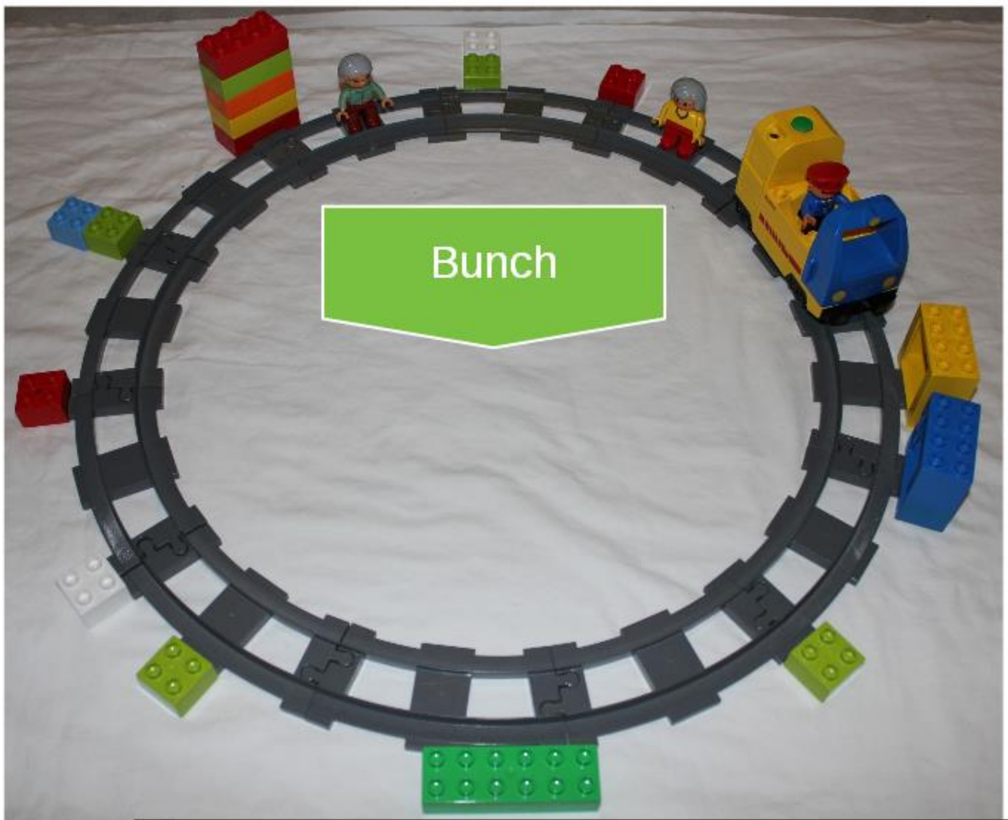

- Load Python packages and modules
- Build linear periodic transfer maps
- Add (collective) kick elements
- Place beam

```
# Bunch
bunch = Bunch(500000, e, gamma, 1.15e11, m_p, 0, beta_x, epsn_x, 0, beta_y, epsn_y, beta_z, sigma_z)
```

introduction to PyHEADTAIL

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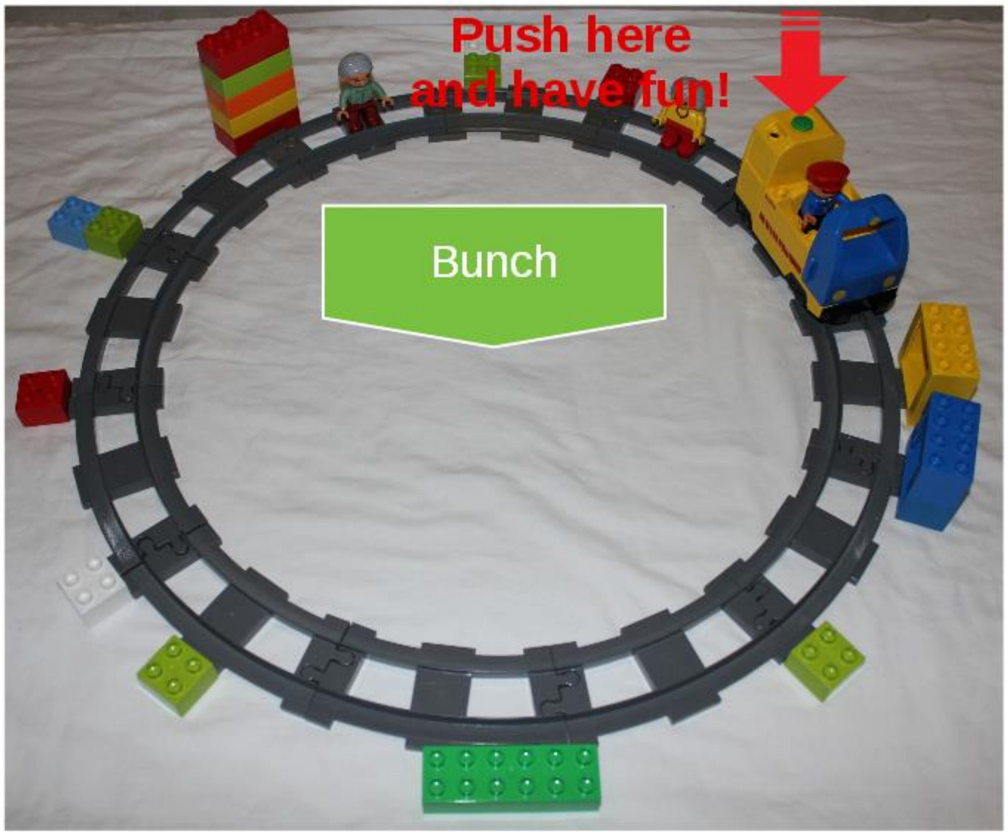
A real world example



- Load Python packages and modules
- Build linear periodic transfer maps
- Add (collective) kick elements
- Place beam

```
for i in range(n_turns):
    for m in map_:
        m.track(bunch)
```

In our case: only RF systems

JUAS

Joint Universities Accelerator School

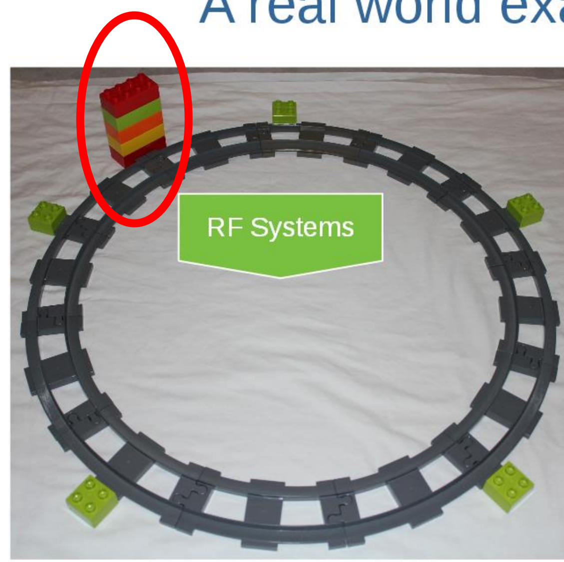
Tracking

- The motion of the particles can be tracked turn by turn using the recurrence relation (between turn *n* and turn *n*+1)

$$\Delta E_{n+1} = \Delta E_n + e\,\hat{V}_{RF}\left[\sin\phi_n - \sin\phi_s\right]$$

$$\phi_{n+1} = \phi_n - \frac{2\,\pi\,h\,\eta}{\beta_s^2\,E_s}\,\Delta E_{n+1}$$

A real world example



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Structure of the ipython file

Import needed libraries

```
In [ ]: import sys
sys.path.append("../../../")
import numpy as np
from scipy.constants import m_p, c, e
from PyHEADTAIL.particles.particles import Particles
import PyHEADTAIL.particles.generators as generators
from PyHEADTAIL.trackers.transverse_tracking import TransverseMap
from PyHEADTAIL.trackers.simple_long_tracking import RFSystems, LinearMap
import PyHEADTAIL.cobra_functions.stats as st
import matplotlib.pyplot as plt
```

Set beam and machine parameters

Define RF system

Generate a matched distribution corresponding to these parameters

```
In [ ]: # general simulation parameters
n_particles = 1000
n_segments = 1

# machine parameters
circumference = 100*2*np.pi
inj_alpha_x = 0#-1.2
inj_alpha_y = 0#15
inj_beta_x = 16.#5.9 # in [m]
inj_beta_y = 16.#5.7 # in [m]
Qx = 6.25
Qy = 6.25
gamma_tr = 6.1
alpha_c_array = [gamma_tr**-2]
V_rf = 20e3 # in [V]
harmonic = 8
phi_offset = 0 # measured from aligned focussing phase (0 or pi)
#pipe_radius = 5e-2
Bdot=0 # in T/s
bending_radius=70 # in m

# beam parameters
Ekin = 1.4e9 # in [eV]
intensity = 8e12
epsn_x = 5e-6 # in [m*rad]
epsn_y = 5e-6 # in [m*rad]
#epsn_z = 1. # 4pi*sig_z*sig_dp (*p0/e) in [eVs]

# calculations
gamma = 1 + e * Ekin / (m_p * c**2)
beta = np.sqrt(1 - gamma**-2)
print('beta: ' + str(beta))
eta = alpha_c_array[0] - gamma**-2
print('eta: ' + str(eta))
if eta < 0:
    phi_offset = np.pi - phi_offset
Etot = gamma * m_p * c**2 / e
p0 = np.sqrt(gamma**2 - 1) * m_p * c
Qs = np.sqrt(np.abs(eta) * V_rf / (2 * np.pi * beta**2 * Etot))
print('Qs: ' + str(Qs))
beta_z = np.abs(eta) * circumference / (2 * np.pi * Qs)
print('beta_z: ' + str(beta_z))
turn_period = circumference / (beta * c)
p_increment_0= e*bending_radius*Bdot*turn_period
sigma_z_0= 230e-9/4*beta*c/10

# BETATRON
# Loop on number of segments and create the TransverseSegmentMap
# for each segment.
s = np.arange(0, n_segments + 1) * circumference / n_segments
alpha_x = inj_alpha_x * np.ones(n_segments)
beta_x  = inj_beta_x * np.ones(n_segments)
D_x     = np.zeros(n_segments)
alpha_y = inj_alpha_y * np.ones(n_segments)
beta_y  = inj_beta_y * np.ones(n_segments)
D_y     = np.zeros(n_segments)

# Define RF systems
rfsystems = RFSystems(circumference, [harmonic], [V_rf], [phi_offset],
                      alpha_c_array, gamma, p_increment=p_increment_0)
# Generate the particle distribution
bunch = generators.ParticleGenerator(macroparticlenumber=n_particles,
                                     intensity=intensity, charge=e, mass=m_p,
                                     circumference=circumference, gamma=gamma,
                                     distribution_x=generators.gaussian2D(epsn_x), alpha_x=inj
                                     distribution_y=generators.gaussian2D(epsn_y), alpha_y=inj
                                     distribution_z=generators.RF_bucket_distribution(rfsystem
                                     ).generate()
```

Loop over number of turns

track

monitor

plot

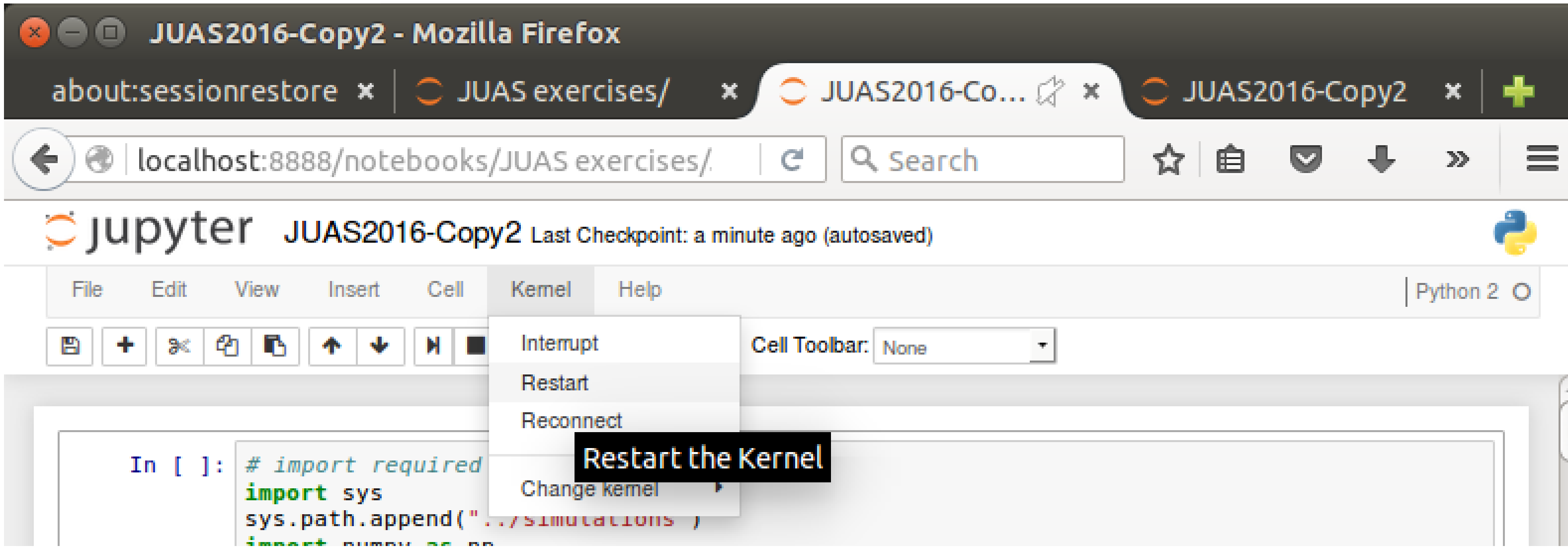
```
In [ ]: # plot phase space
plt.close()
plt.ion()
fig = plt.figure(1)
for i in np.arange(0, 50, 1):
    # track the particles
    rfsystems.track(bunch)
    if i%10 == 0:
        # monitor the particles
        bucket = rfsystems.get_bucket(gamma=bunch.gamma)

        # plot the RF bucket envelope
        z = np.linspace(*bucket.interval, num=100)
        dp = np.linspace(-0.005, 0.005, num=100)
        ZZ, DPP = np.meshgrid(z, dp)
        HH = bucket.hamiltonian(ZZ, DPP)
        plt.contour(ZZ, DPP, HH, levels=[0], colors='magenta')

        # plot the particles in phase space
        plt.plot(bunch.z, bunch.dp, 'o')
        plt.xlabel('z in m')
        plt.ylabel('Delta p/p')
        plt.show()
        plt.pause(0.1)
        plt.cla()
plt.ioff()
```

ipython cheat sheet

- To restart the kernel at any point: “Kernel” → “Restart”



- To only interrupt the kernel: “Kernel” → “Interrupt”
- Shift-enter: execute current cell and move to next cell
- Ctrl-enter: execute current cell and stay on current cell

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Tracking example: injection energy

- nTOF bunch in the CERN PS (near transition)

Average machine radius: R [m]	100
Bending dipole radius: ρ [m]	70
$\dot{B}$ [T/s]	0
$\hat{V}_{RF}$ [kV]	200
h	8
α_p	0.027
Longitudinal (total) emittance: ε_L [eVs]	2
Number of protons/bunch: N_b [1E10 p/b]	800
Norm. rms. transverse emittance: $\varepsilon^*_{x,y}$ [µm]	5
Trans. average betatron function: $\beta_{x,y}$ [m]	16
Beam pipe [cm × cm]	3.5 × 7
Trans. tunes: $Q_{x,y}$	6.25

20 kV at injection

=> $\gamma_t \approx 6.1$

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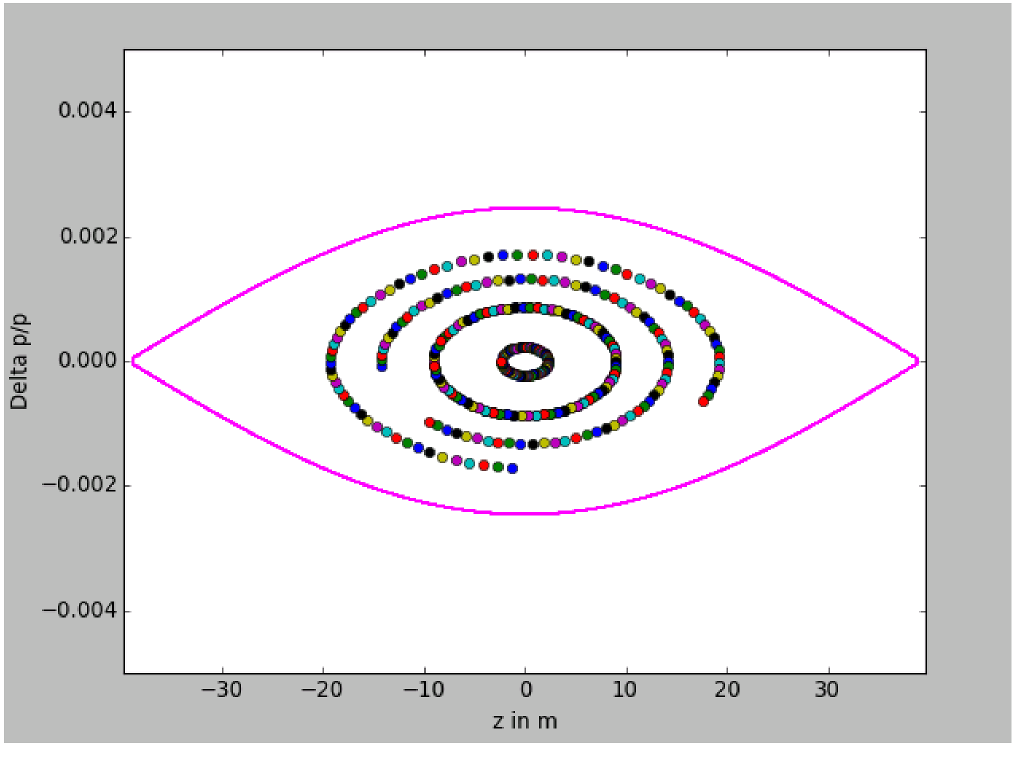
20 kV at injection

=> $\gamma_t \approx 6.1$

```
Ekin = 1.4e9 # in [eV]
circumference = 100*2*np.pi
bending_radius=70 # in m
Bdot=0 # in T/s
V_rf = 20e3 # in [V]
harmonic = 8
gamma_tr = 6.1
sigma_z_0= 230e-9/4*beta*c
```

Let’s run that example

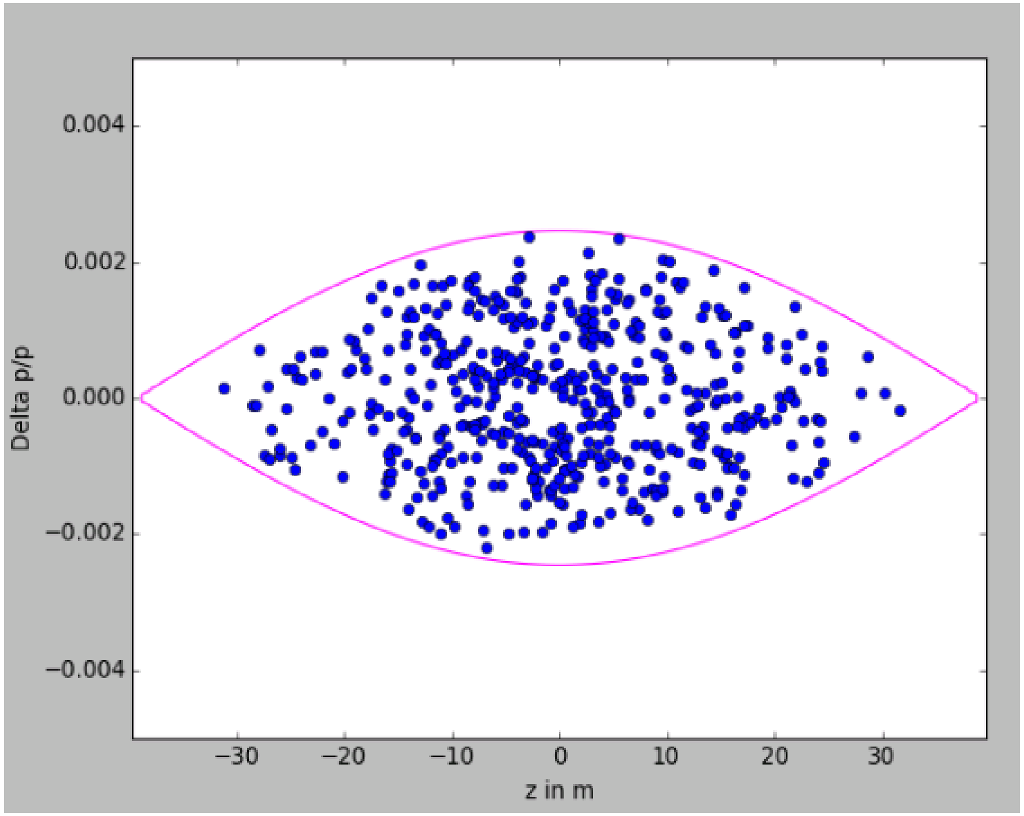
- Use a small number of particles (n_particles~ 10) to observe the synchrotron motion at large and small amplitudes



→ Can you estimate the synchrotron tune Qs? Is it consistent with the course?

Synchrotron motion

- Use a larger number of particles (~500) and reset the graph every time ("plt.cla()" uncommented)



→ Are the particles rotating in the correct direction?
→ Plot the phase space as in the course (in ϕ[degrees], ΔE [MeV])
→ Is the maximum energy consistent with the course?

Top energy

- What parameters should be changed for top energy (still no acceleration and h=8)?
- What changes in the plot compared to injection energy?

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    - Impact of voltage mismatch
    - Impact of acceleration
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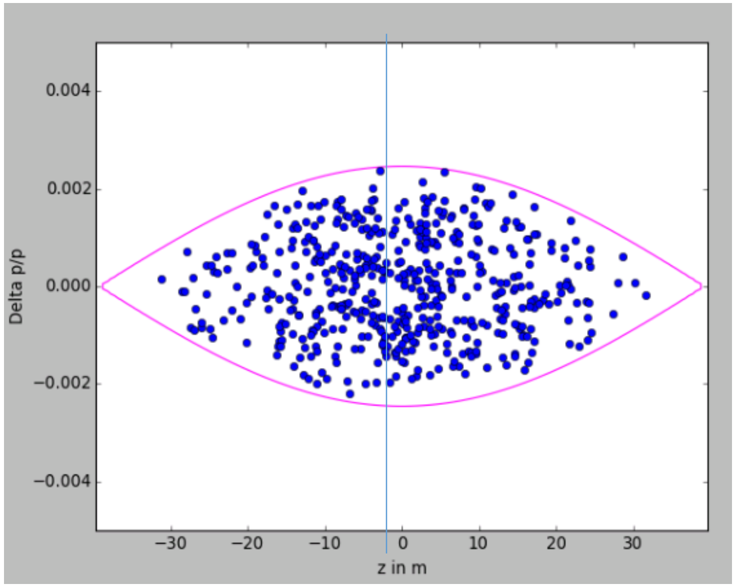
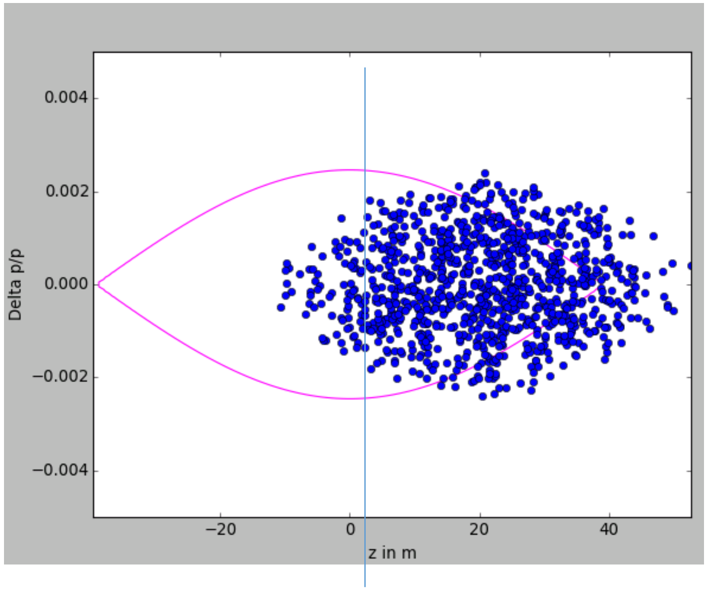
Impact of phase mismatch

- Generate ~1000 particles
- Add e.g. 5 or 20 m to all particles: `bunch.z =bunch.z+5`
- Track particles for ~5000 turns
- Plot the distribution every 100 turns: `if i%100 == 0:`

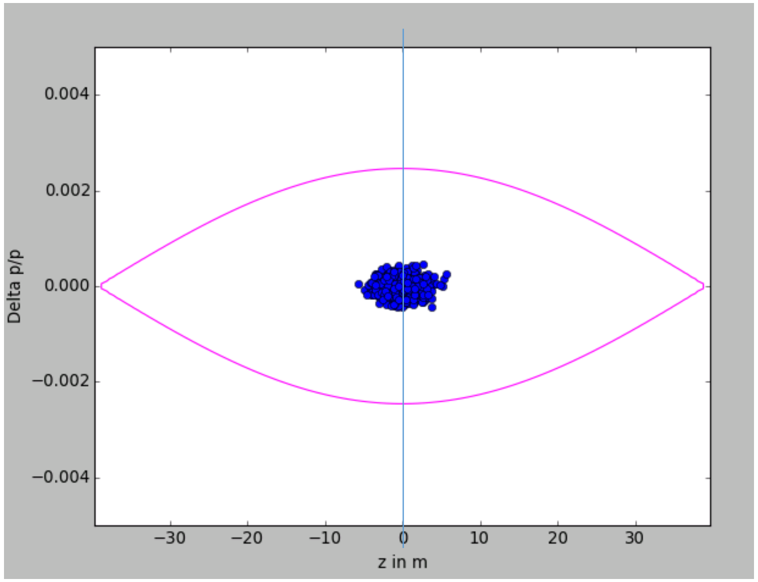


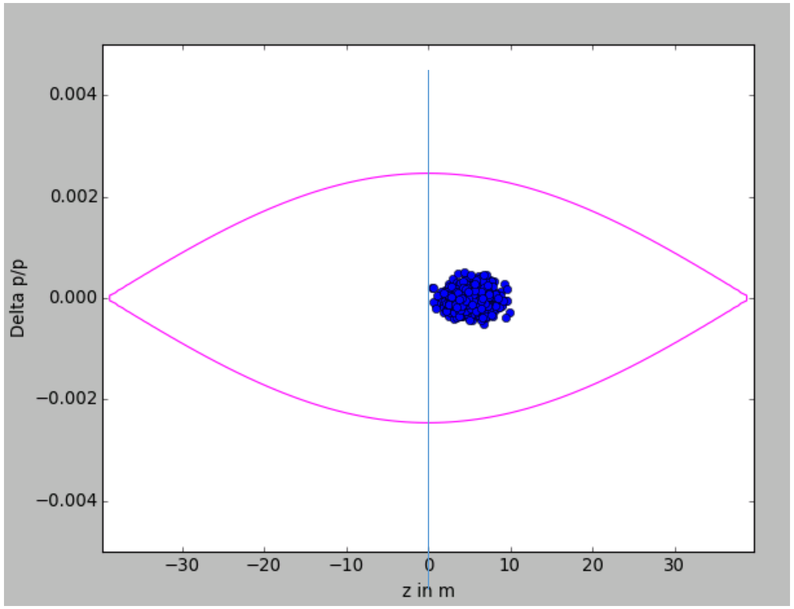


→ What will happen?

Impact of phase mismatch

- Use a smaller bunch length (e.g. divide by 10)
- Generate ~1000 particles
- Add e.g. 5m to all particles: `bunch.z =bunch.z+5`
- Track particles for ~5000 turns
- Plot the distribution every 100 turns: `if i%100 == 0:`





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- Use ~1000 particles
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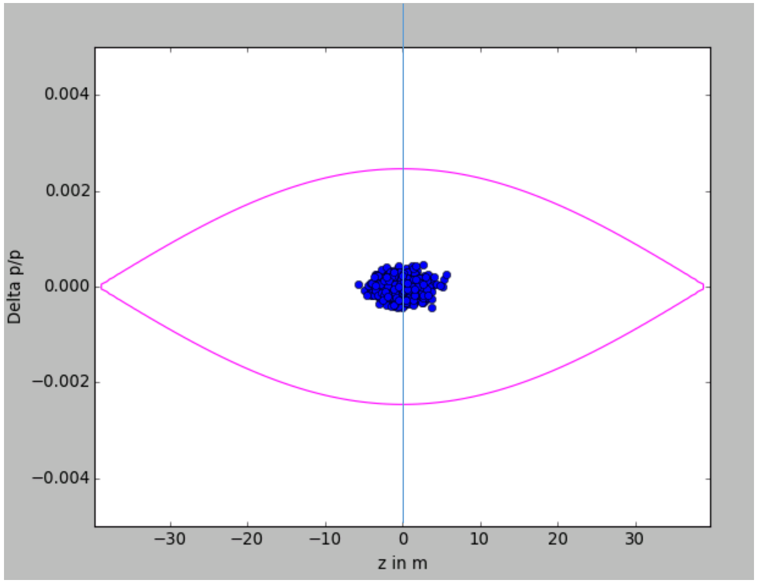
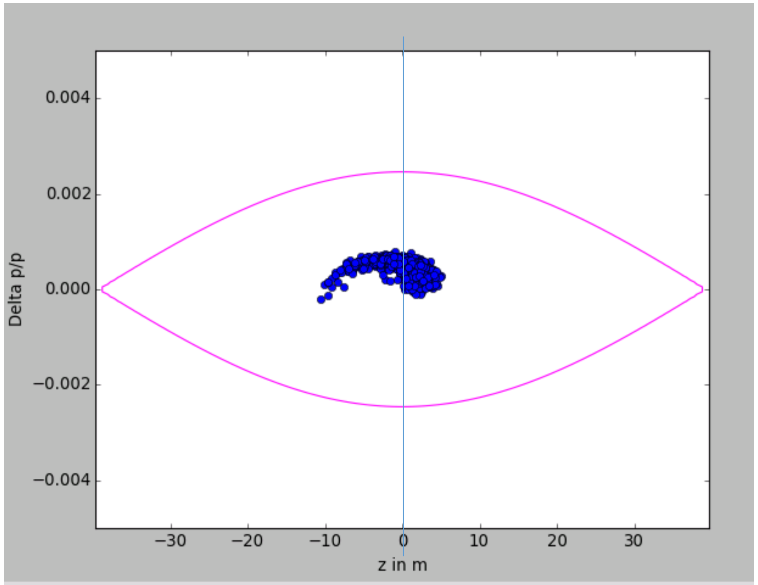
- Plot the distribution every 100 turns: `if i%100 == 0:`

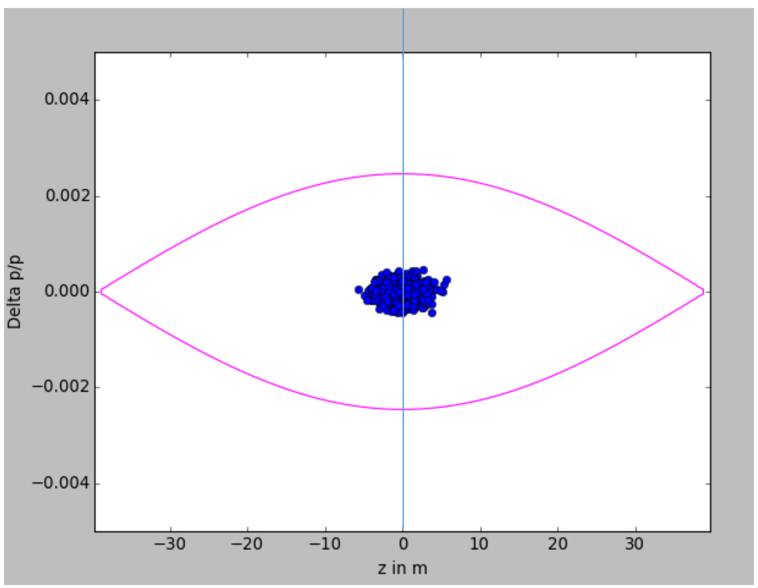


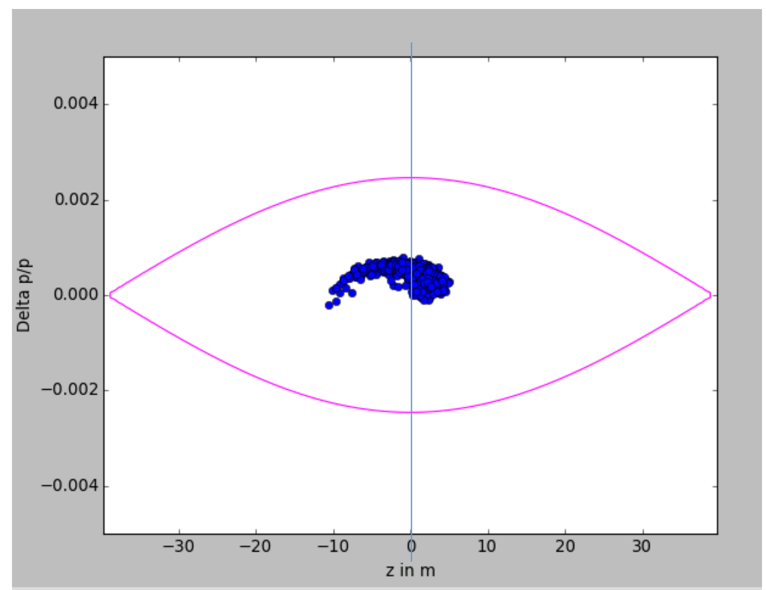


→ Filamentation and eventually?

Impact of phase mismatch

- Use a smaller bunch length (e.g. divide by 10)
- Use ~1000 particles
- Add e.g. 5m to all particles:
- Track particles for ~500000 turns
- Plot the distribution every 1000 turns

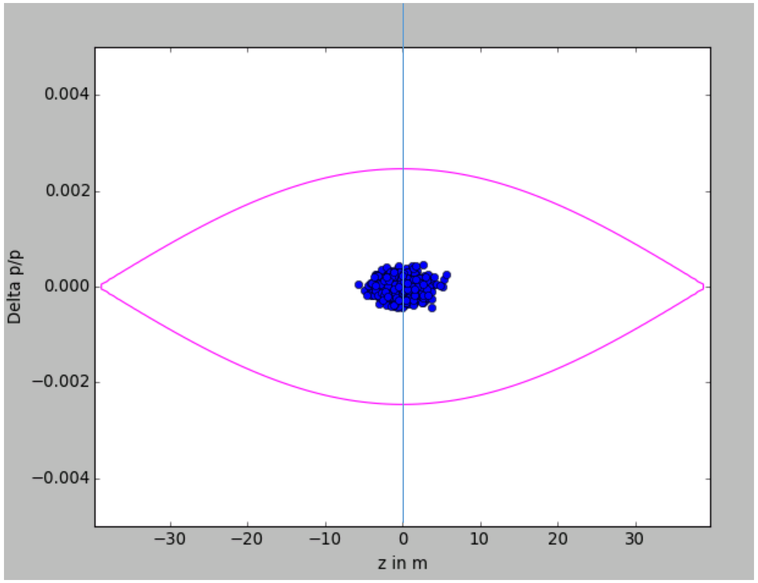


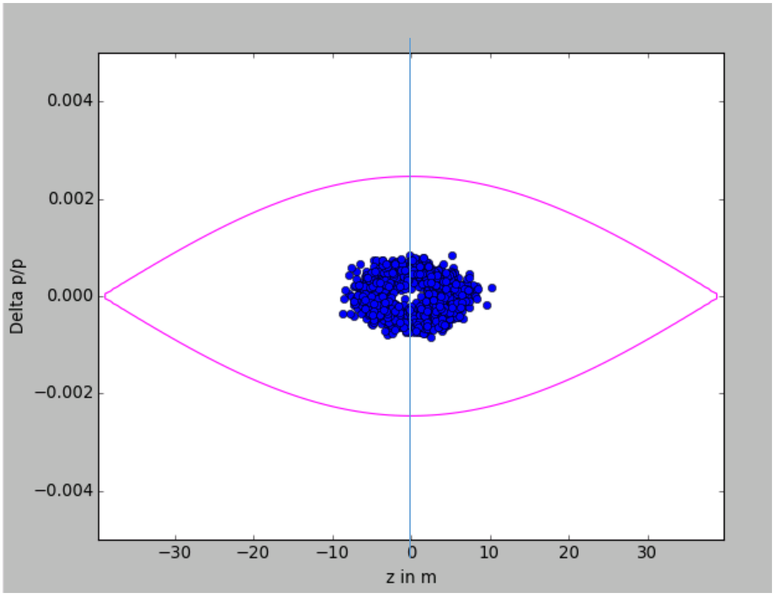


→ Filamentation and eventually?

Impact of phase mismatch

- Use a smaller bunch length (e.g. divide by 10)
- Use ~1000 particles
- Add e.g. 5m to all particles:
- Track particles for ~500000 turns
- Plot the distribution every 100 turns:





→ Eventually emittance growth
→ Try also with larger mismatch (20 m)

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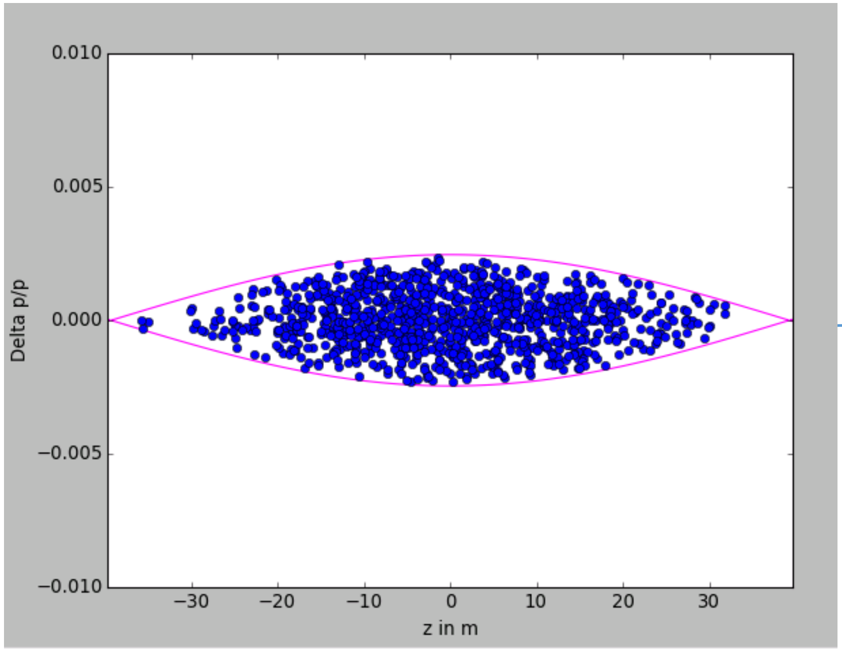
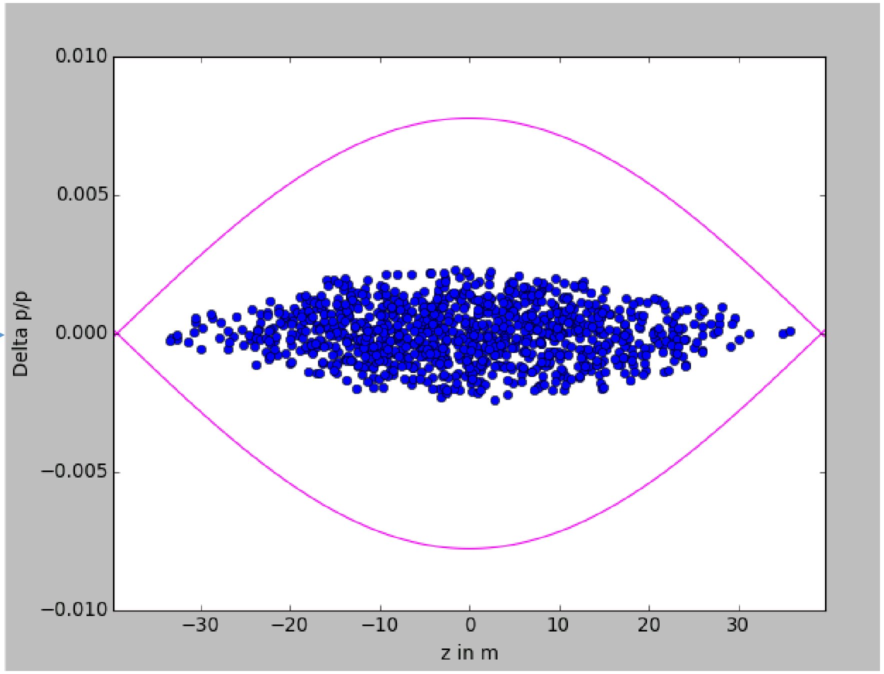
Impact of voltage mismatch (too high)

- Use the nominal bunch length
- track 1000 particles for 500 turns (plot every 10 turns)
- Change V_RF to V_RF*10 after the bunch is matched to V_RF

```
# Define RF systems
rfsystems = RFSystems(circumference, [harmonic], [V_rf*10], [phi_offset],
                      alpha_c_array, gamma, p_increment=p_increment_0)
```





→ What will happen?

Impact of voltage mismatch (too high)

- Use the nominal bunch length
- track 1000 particles for 500 turns (plot every 10 turns)
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```
# Define RF systems
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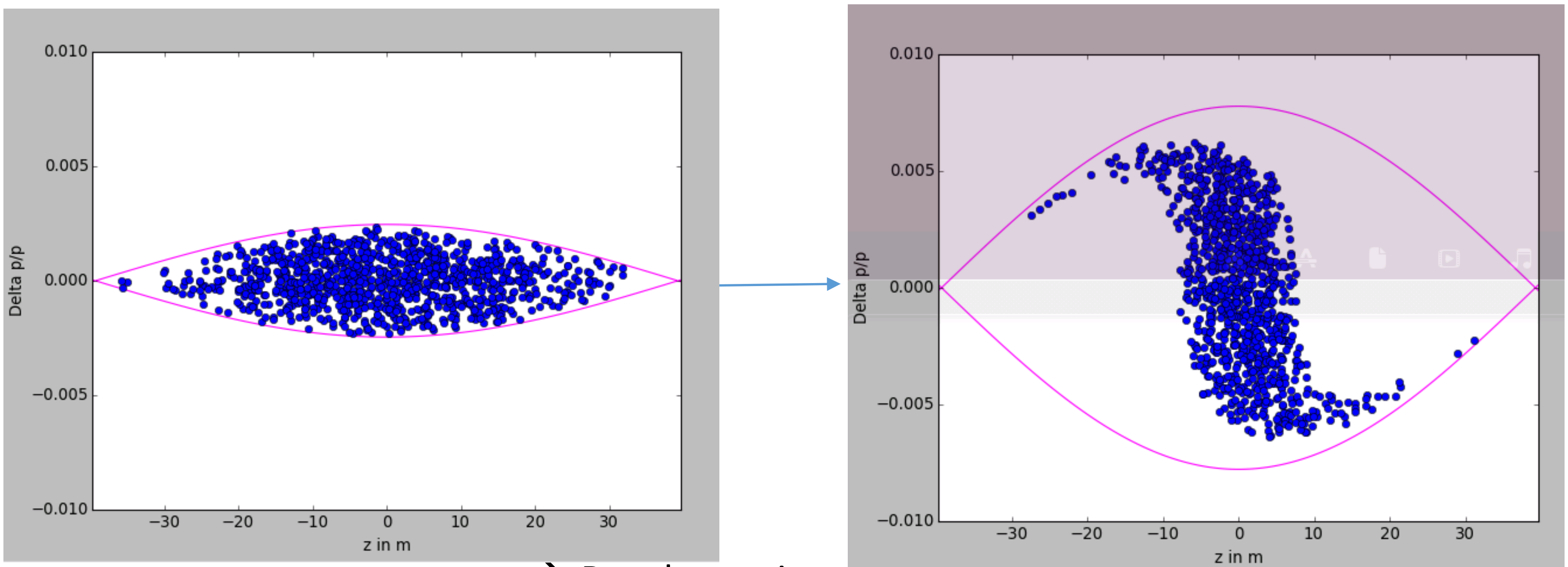


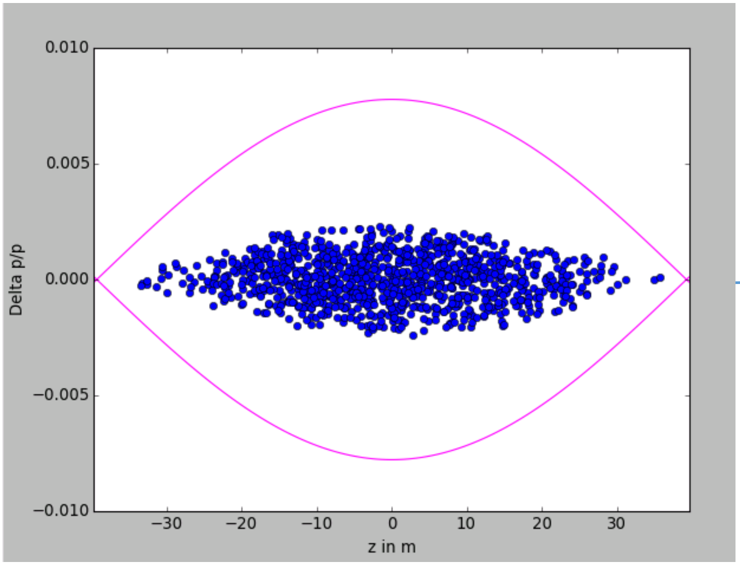
→ Bunch rotation

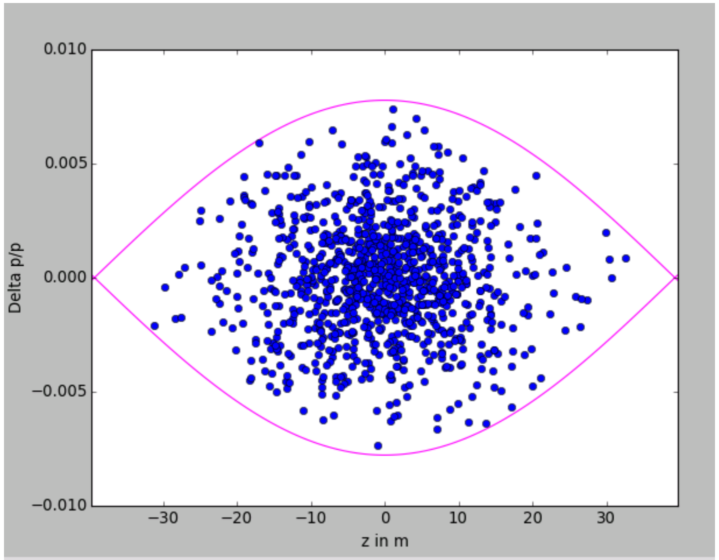
→ Bunch shortening, if phased correctly, but…

Impact of voltage mismatch (too high)

- Use the nominal bunch length
- track 1000 particles for 5000 turns (plot every 100 turns)
- Change V_RF to V_RF*10 after the bunch is matched to V_RF

```
# Define RF systems
rfsystems = RFSystems(circumference, [harmonic], [V_rf*10], [phi_offset],
                      alpha_c_array, gamma, p_increment=p_increment_0)
```



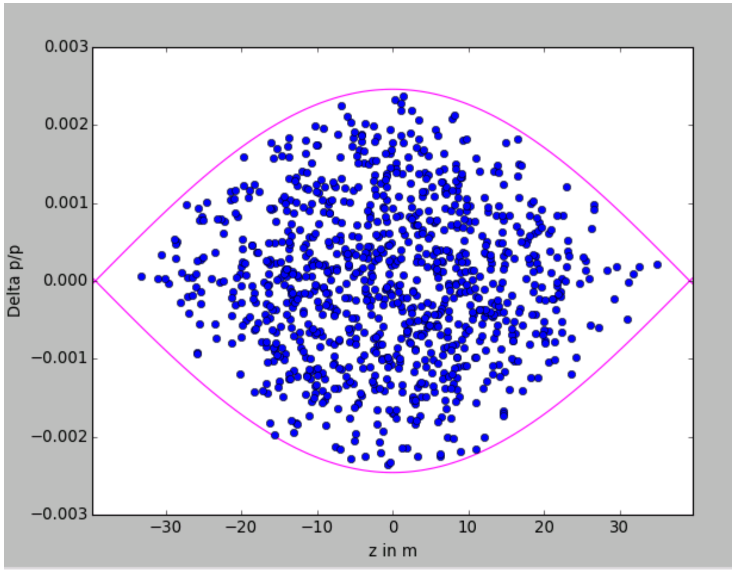


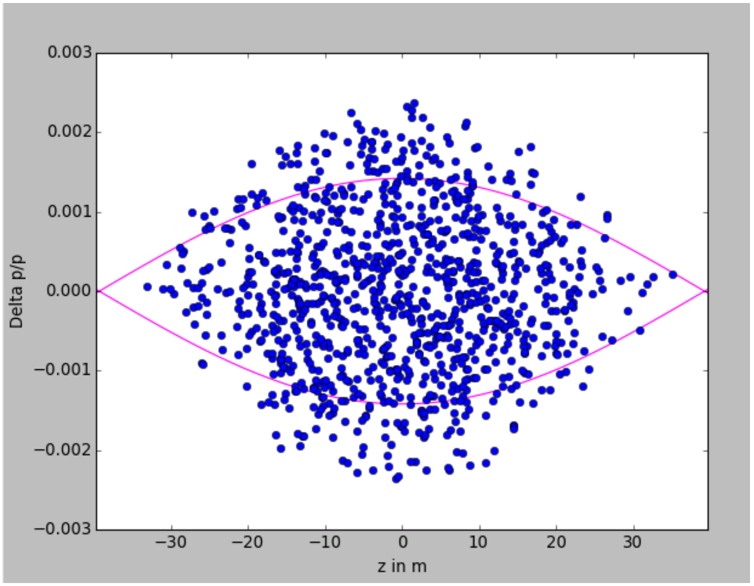
→ But should not wait too long!

→ Emittance growth!

Impact of voltage mismatch (too low)

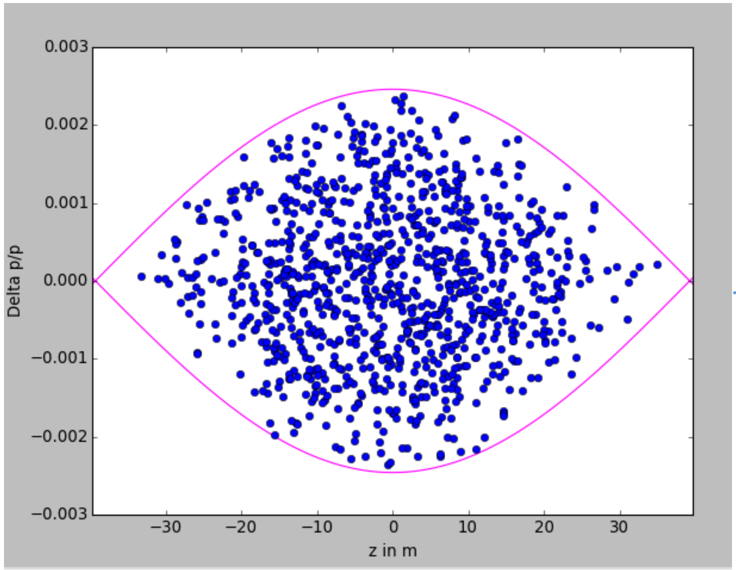
- Use the nominal bunch length
- track 1000 particles for 500 turns (plot every 10 turns)
- Change V_RF to V_RF/10 after the bunch is matched to V_RF
- Adapt the deltap plotting limits

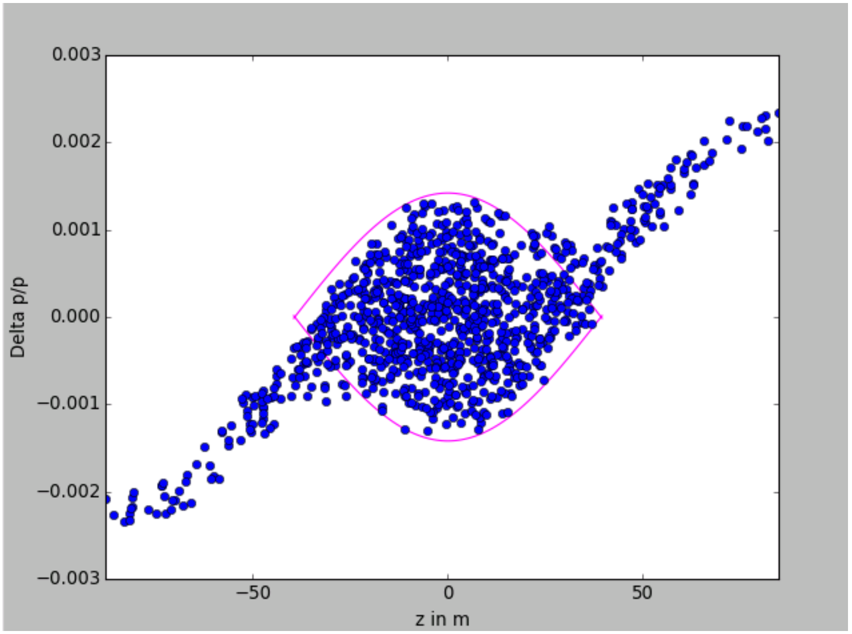




Impact of voltage mismatch (too low)

- Use the nominal bunch length
- track 1000 particles for 500 turns (plot every 10 turns)
- Change V_RF to V_RF/10 after the bunch is matched to V_RF
- Adapt the deltap plotting limits





Agenda

- Goals
- Plan
- Introduction to PyHEADTAIL
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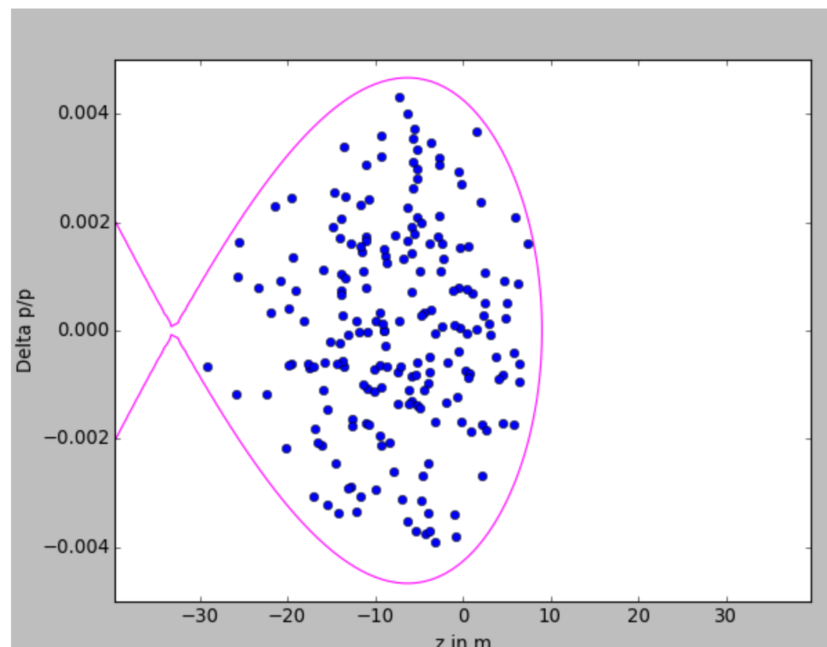
Impact of acceleration

- Use the nominal bunch length
- Use 200 particles
- Use Bdot=2.2 T/s
- Does it work? Why?

Impact of acceleration

- Use the nominal bunch length
- Use 1000 particles
- Use Bdot=2.2 T/s
- Change VRF to 200 kV
- Compute the synchronous phase
- Plot the phase space in in ϕ[degrees], ΔE [MeV]



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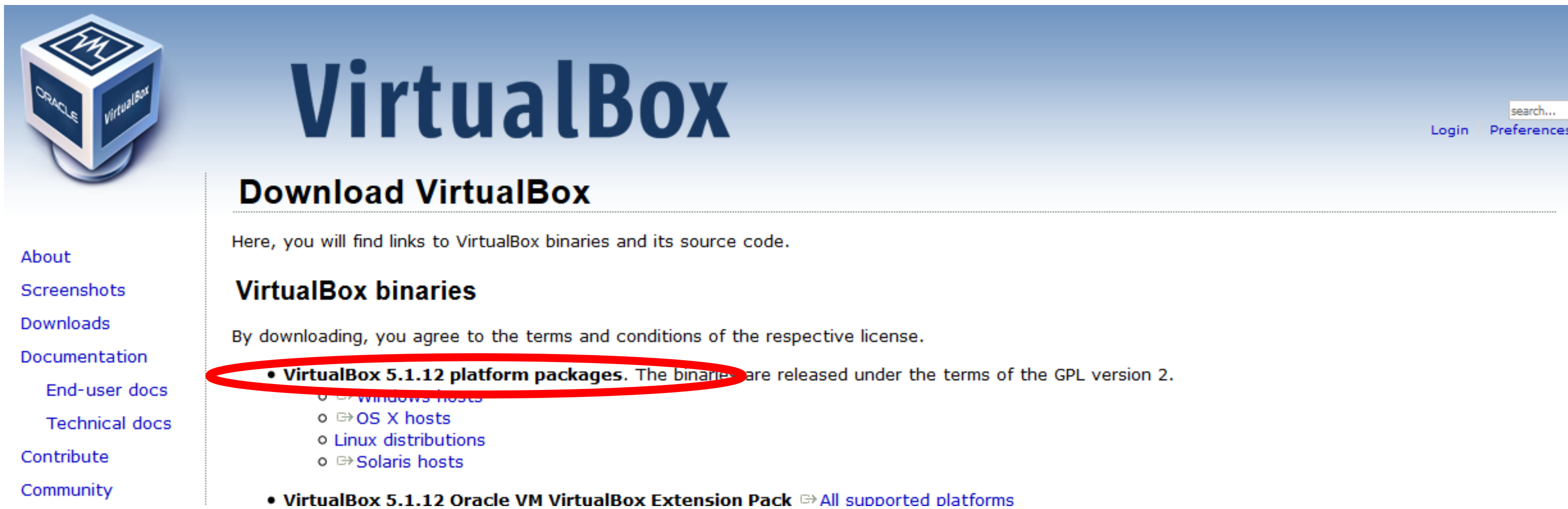
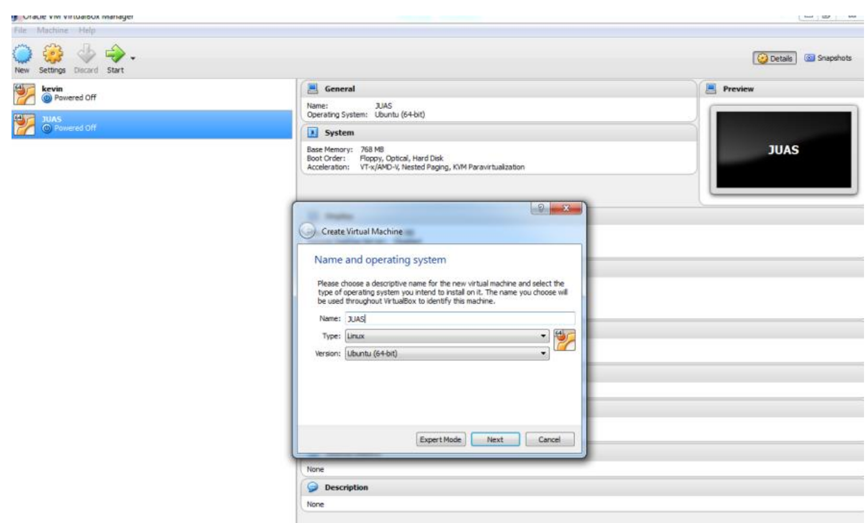
Setting up the operating system

- Install a virtual box to get an Ubuntu environment

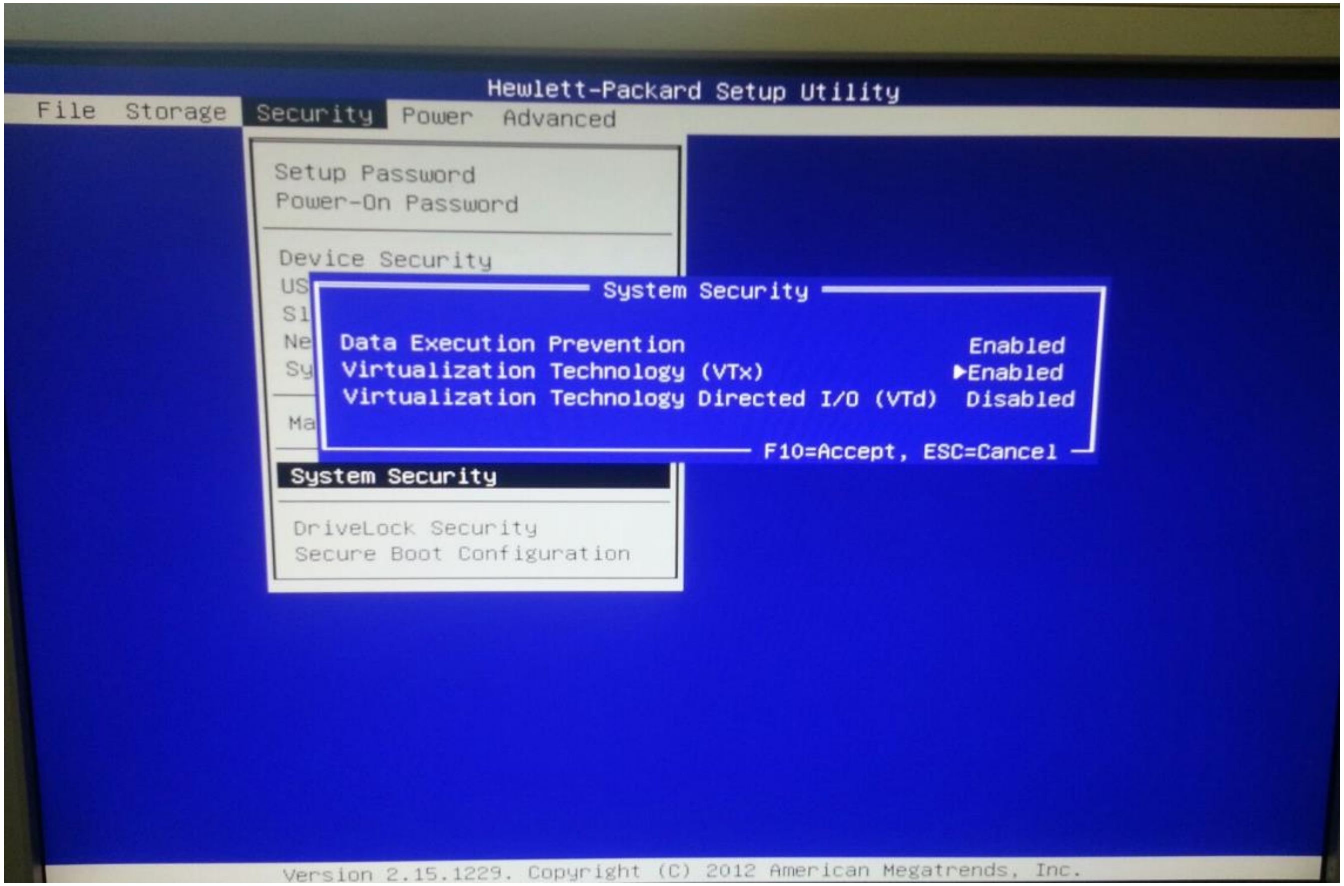
  Ex: https://www.virtualbox.org/wiki/Downloads



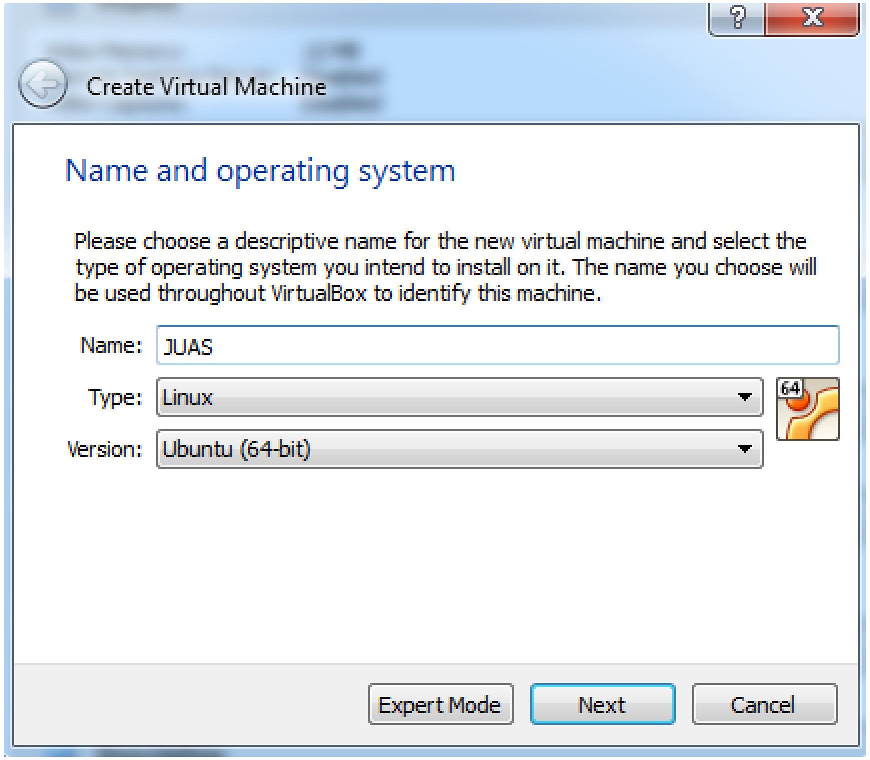


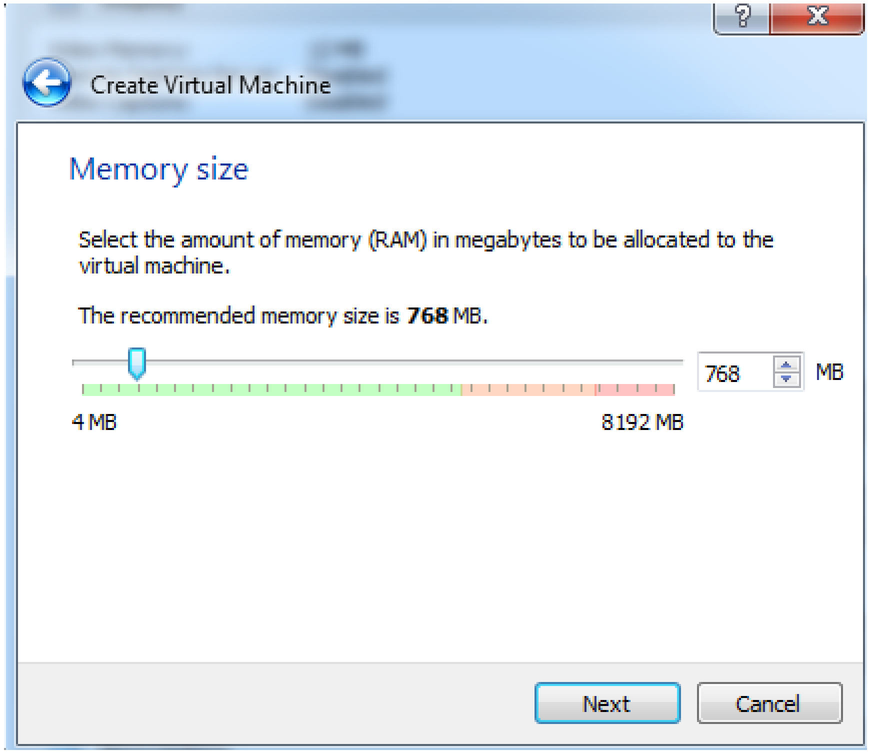
- Create a new virtual machine with Ubuntu 64-bit

In case of a “VTx” error or an impossibility to select 64 bit operating system when launching the virtual machine, one needs to turn Virtualization Technology (VTx) on in the BIOS (see chapter 10.3 in https://www.virtualbox.org/manual/ch10.html#hwvirt)

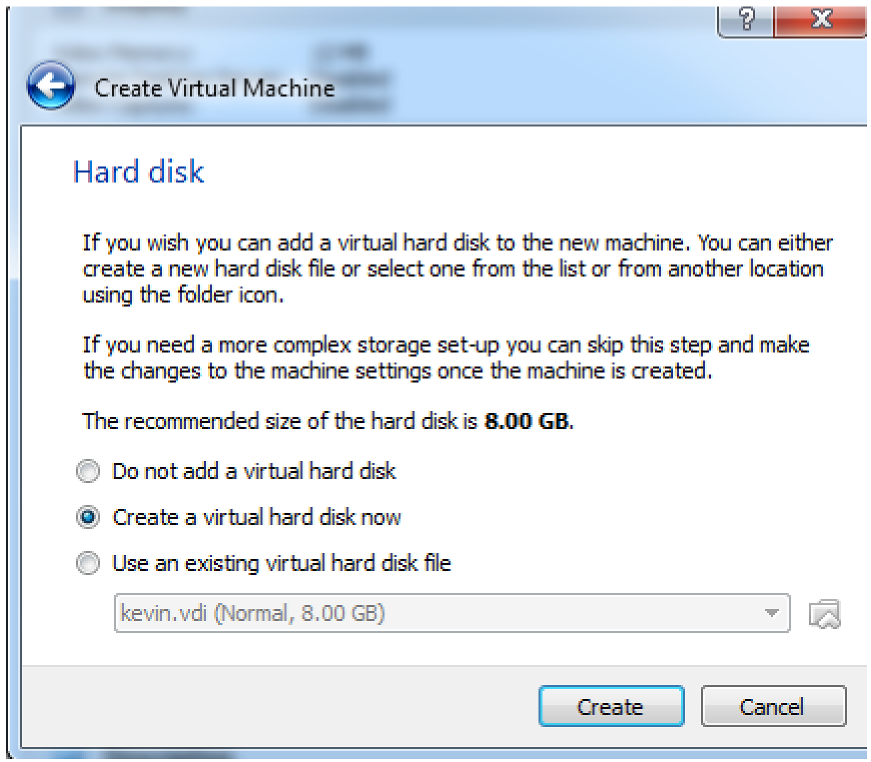


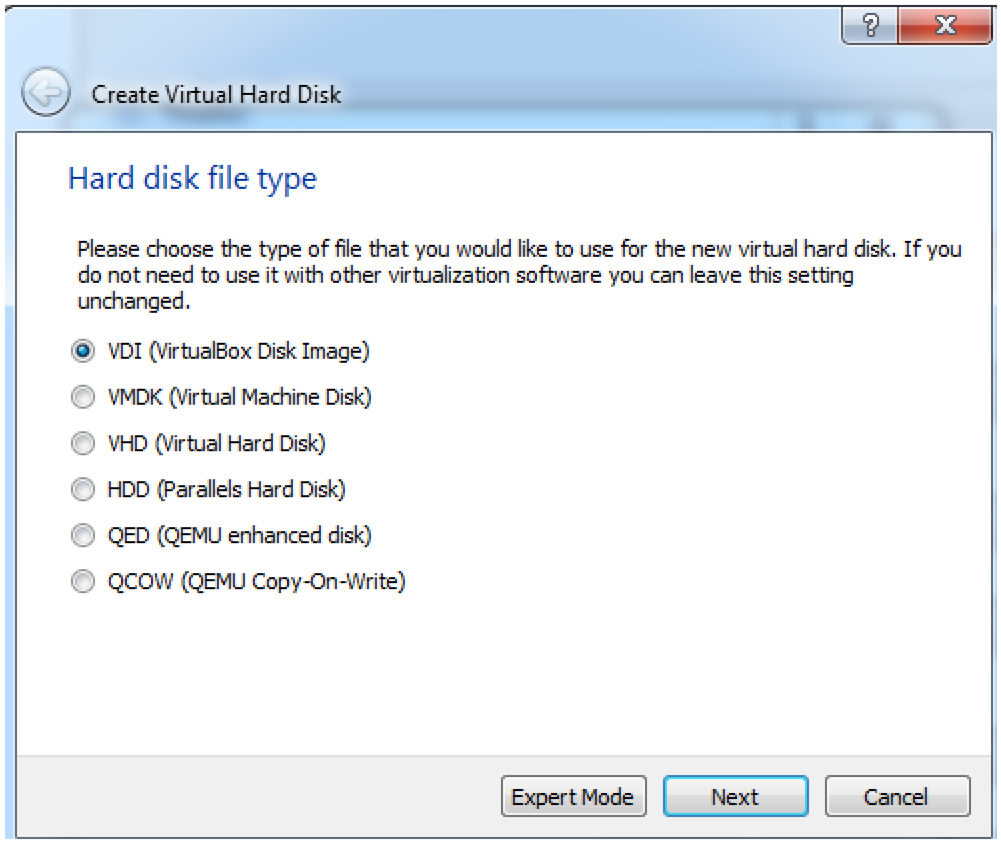
Create virtual machine

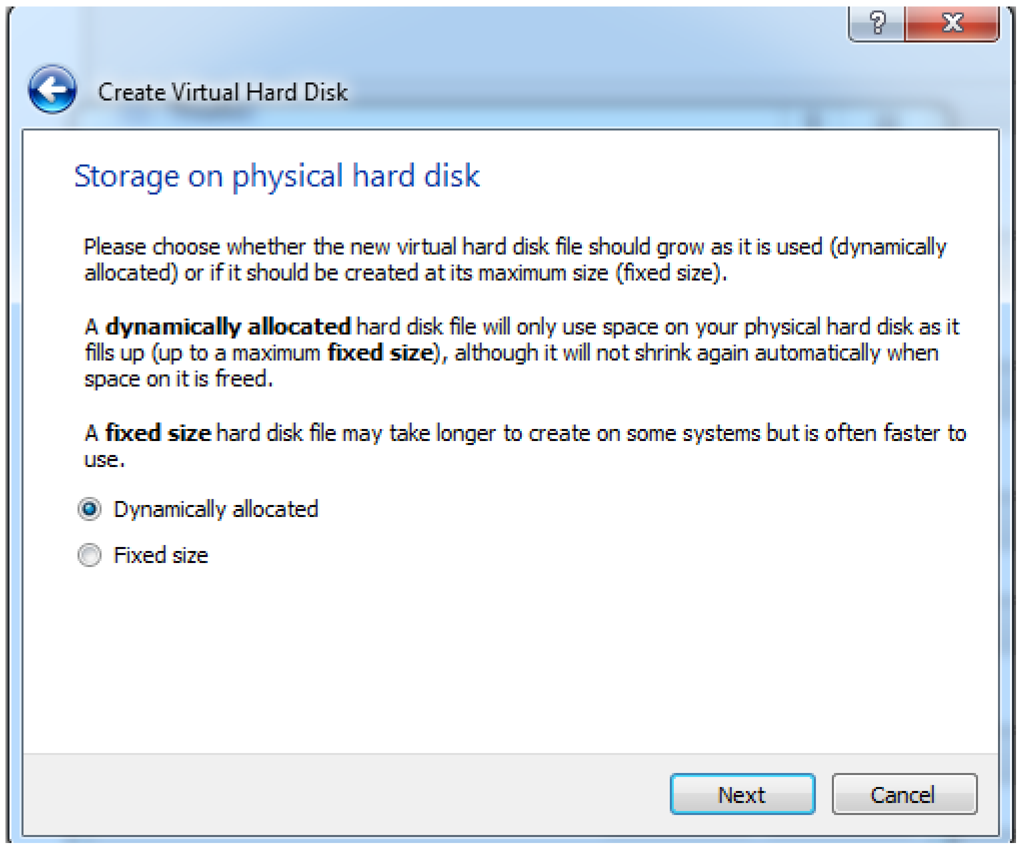


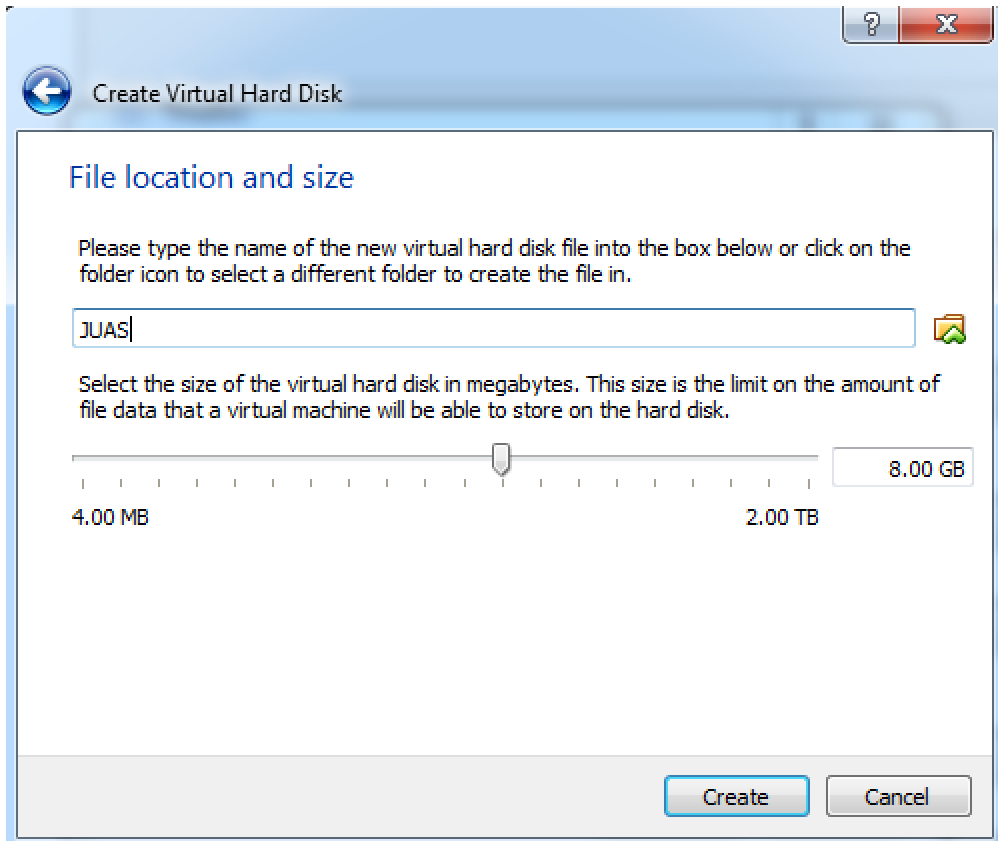


Actually 2 GB is recommended by Ubuntu. This setting can be modified later.


Create Virtual Machine
Hard disk
If you wish you can add a virtual hard disk to the new machine. You can either create a new hard disk file or select one from the list or from another location using the folder icon.
If you need a more complex storage set-up you can skip this step and make the changes to the machine settings once the machine is created.
The recommended size of the hard disk is 8.00 GB.
Do not add a virtual hard disk
Create a virtual hard disk now
Use an existing virtual hard disk file
kevin.vdi (Normal, 8.00 GB)
Create
Cancel

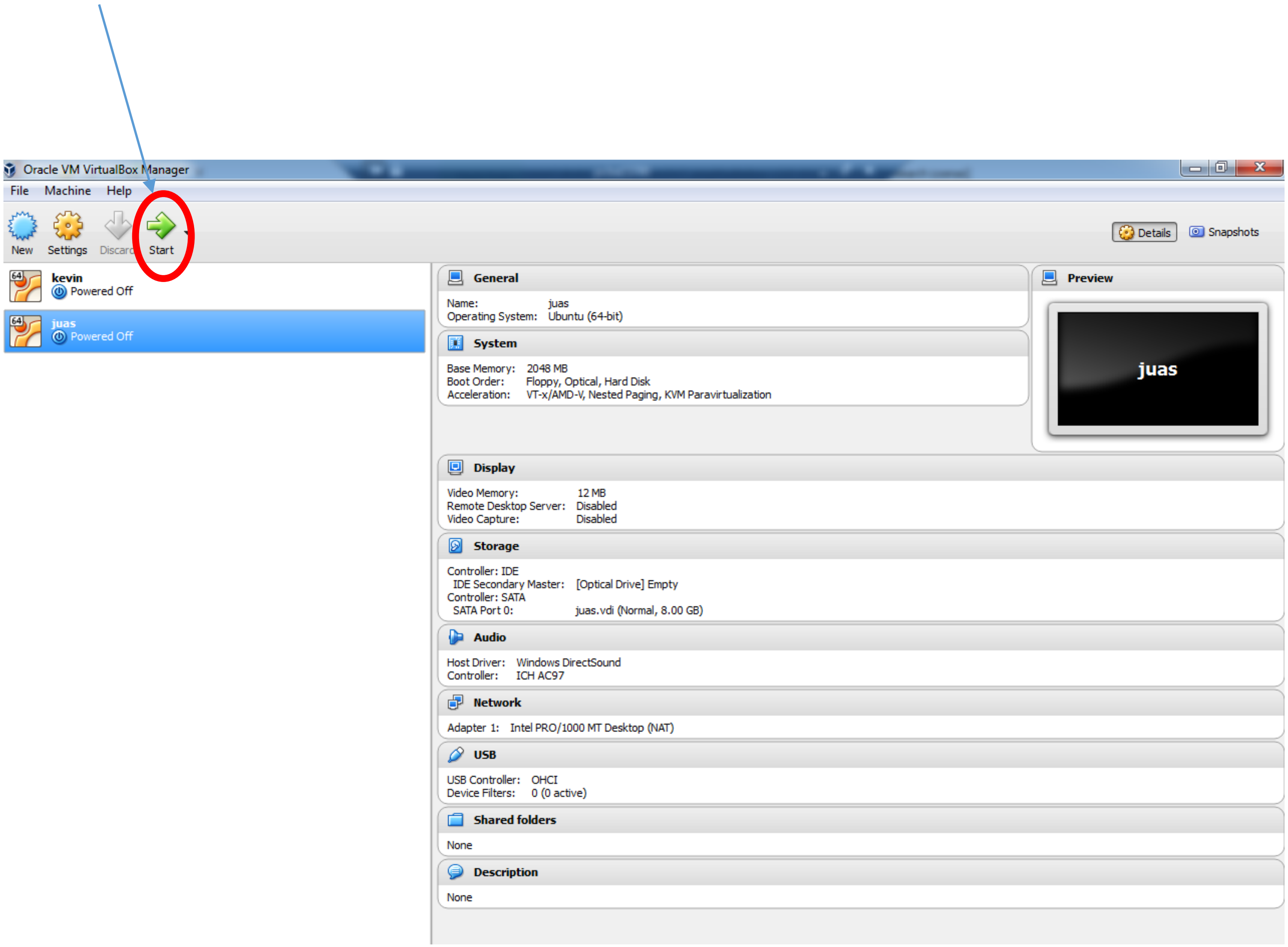

Create Virtual Hard Disk
Hard disk file type
Please choose the type of file that you would like to use for the new virtual hard disk. If you do not need to use it with other virtualization software you can leave this setting unchanged.
VDI (VirtualBox Disk Image)
VMDK (Virtual Machine Disk)
VHD (Virtual Hard Disk)
HDD (Parallels Hard Disk)
QED (QEMU enhanced disk)
QCOW (QEMU Copy-On-Write)
Expert Mode
Next
Cancel


Create Virtual Hard Disk
Storage on physical hard disk
Please choose whether the new virtual hard disk file should grow as it is used (dynamically allocated) or if it should be created at its maximum size (fixed size).
A dynamically allocated hard disk file will only use space on your physical hard disk as it fills up (up to a maximum fixed size), although it will not shrink again automatically when space on it is freed.
A fixed size hard disk file may take longer to create on some systems but is often faster to use.
Dynamically allocated
Fixed size
Next
Cancel



→ Assign 20 GB if possible.

Start the VM



Oracle VM VirtualBox Manager
File
Machine
Help
New
Settings
Discard
Start
Details
Snapshots
kevin
Powered Off
juas
Powered Off
General
Name: juas
Operating System: Ubuntu (64-bit)
System
Base Memory: 2048 MB
Boot Order: Floppy, Optical, Hard Disk
Acceleration: VT-x/AMD-V, Nested Paging, KVM Paravirtualization
Preview
juas
Display
Video Memory: 12 MB
Remote Desktop Server: Disabled
Video Capture: Disabled
Storage
Controller: IDE
IDE Secondary Master: [Optical Drive] Empty
Controller: SATA
SATA Port 0: juas.vdi (Normal, 8.00 GB)
Audio
Host Driver: Windows DirectSound
Controller: ICH AC97
Network
Adapter 1: Intel PRO/1000 MT Desktop (NAT)
USB
USB Controller: OHCI
Device Filters: 0 (0 active)
Shared folders
None
Description
None

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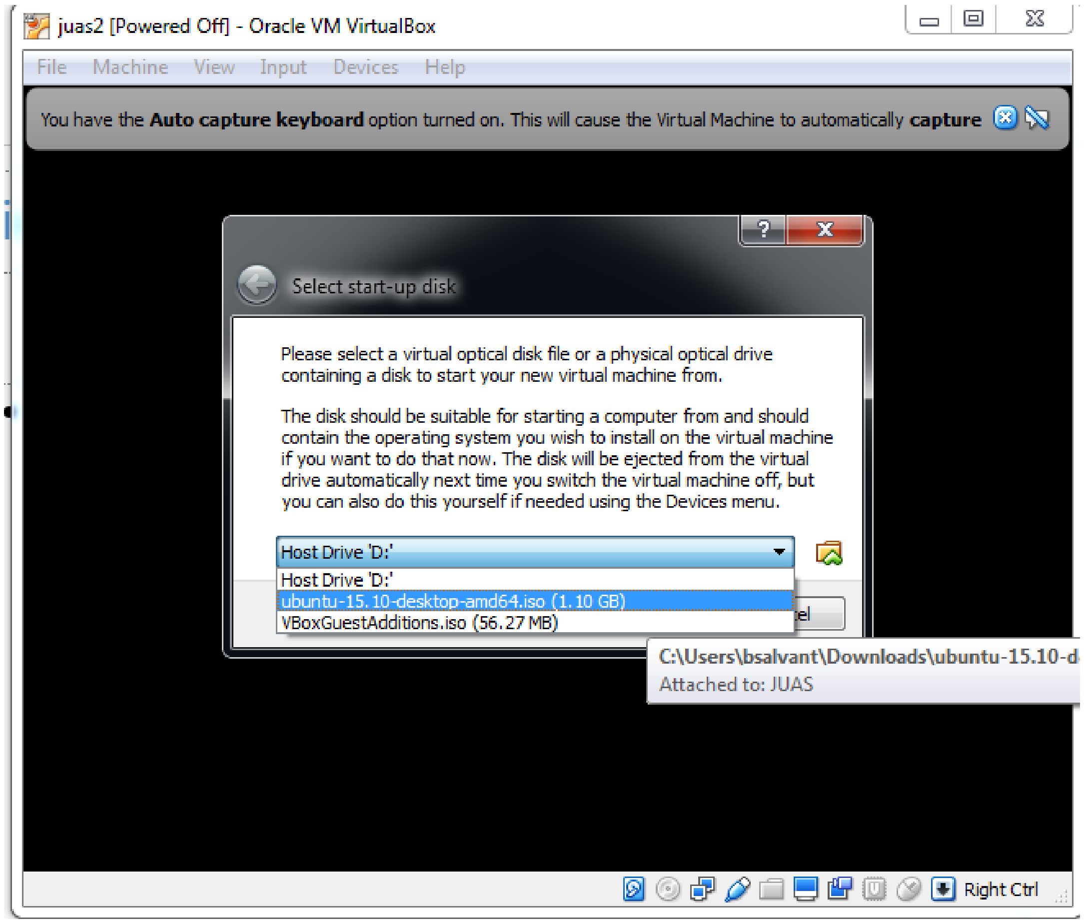
Download ubuntu

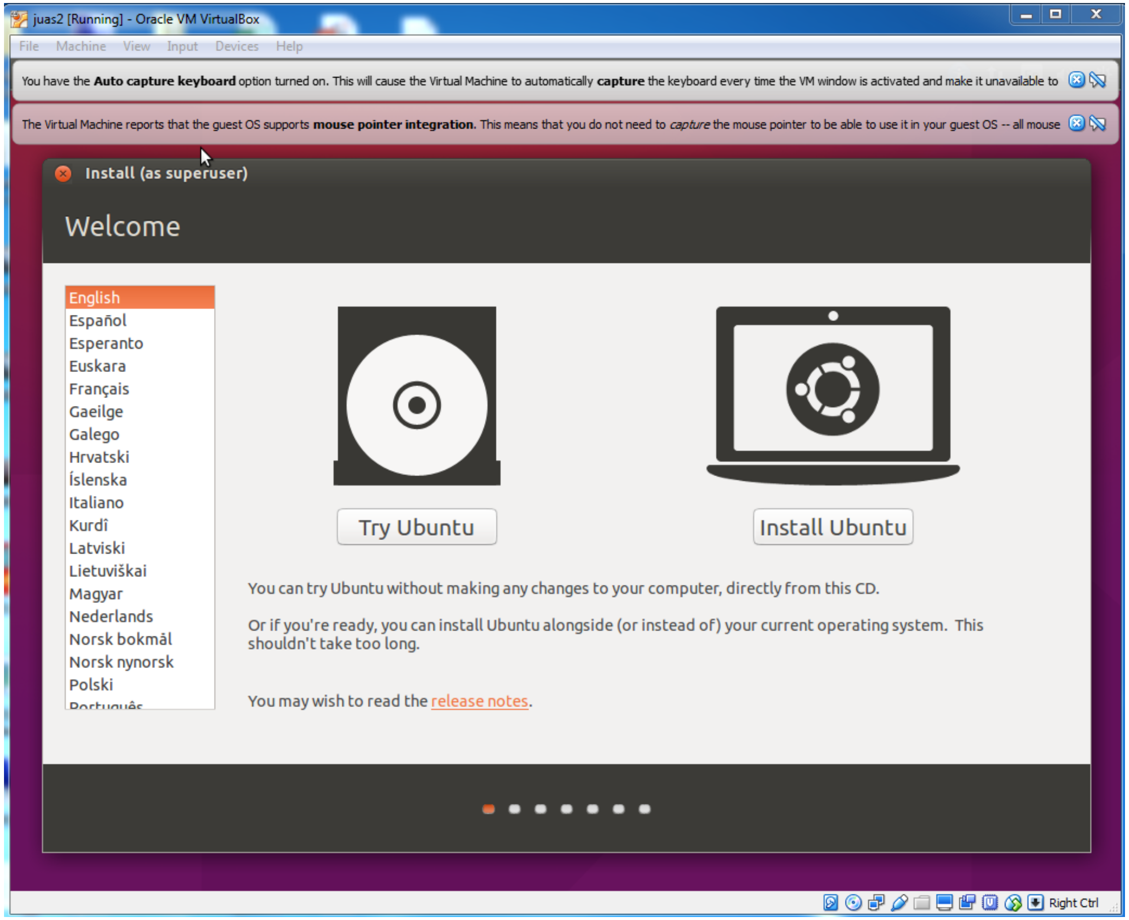
- https://www.ubuntu.com/download/desktop

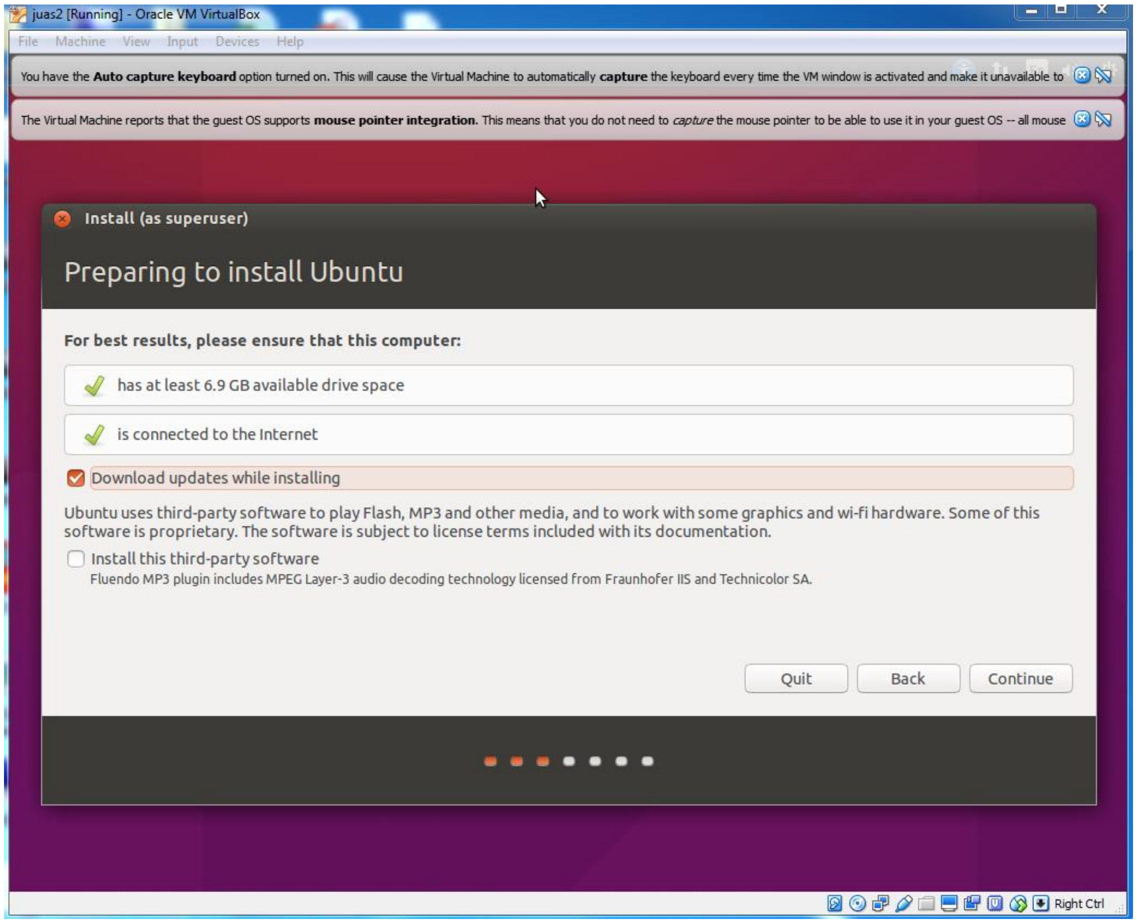
Select Ubuntu start up disk



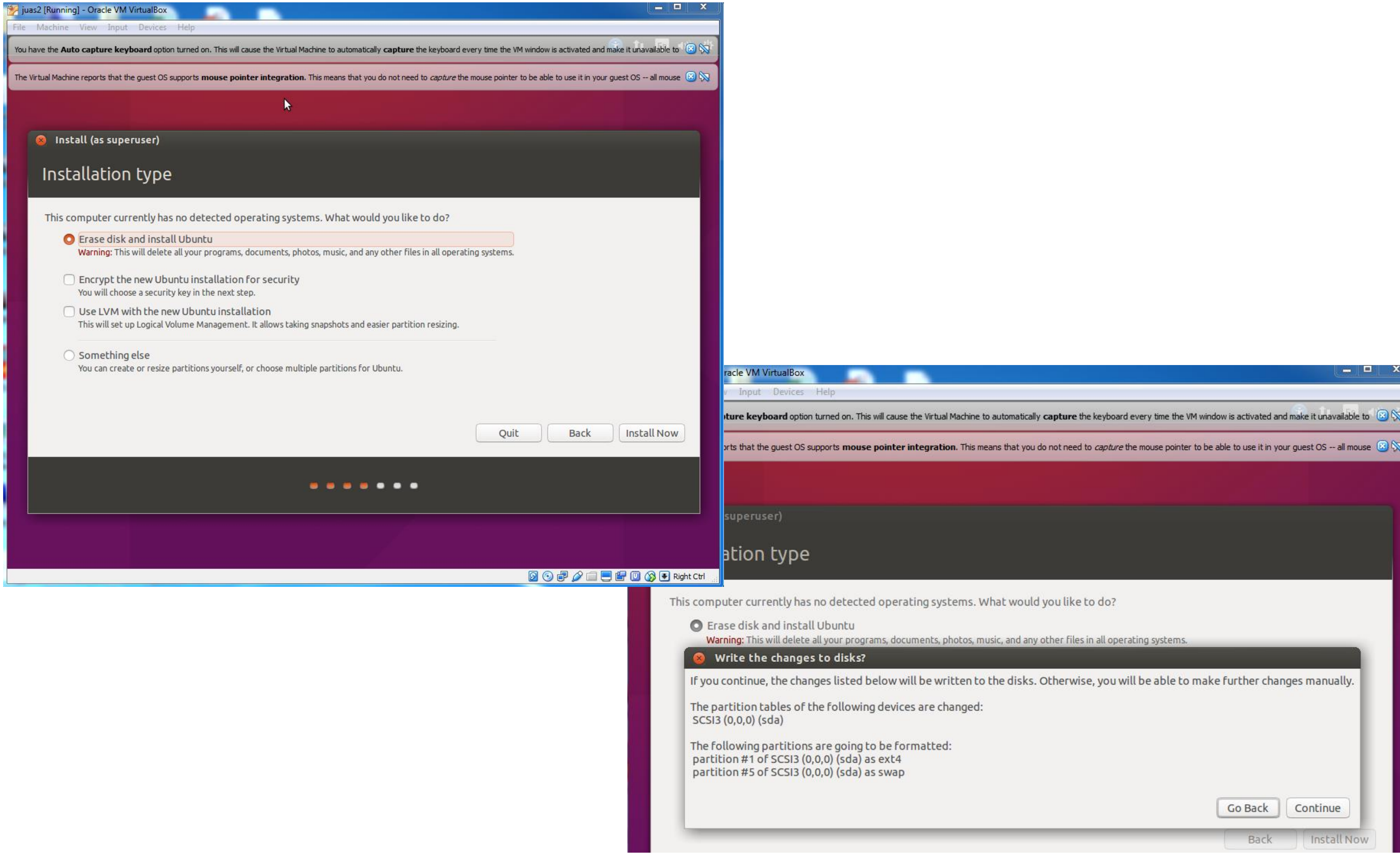
You may have to click on the small green arrow to browse for your Ubuntu installation image

Install ubuntu




juas2 [Running] - Oracle VM VirtualBox
File Machine View Input Devices Help
You have the Auto capture keyboard option turned on. This will cause the Virtual Machine to automatically capture the keyboard every time the VM window is activated and make it unavailable to
The Virtual Machine reports that the guest OS supports mouse pointer integration. This means that you do not need to capture the mouse pointer to be able to use it in your guest OS -- all mouse
Install (as superuser)
Preparing to install Ubuntu
For best results, please ensure that this computer:
has at least 6.9 GB available drive space
is connected to the Internet
Download updates while installing
Ubuntu uses third-party software to play Flash, MP3 and other media, and to work with some graphics and wi-fi hardware. Some of this software is proprietary. The software is subject to license terms included with its documentation.
Install this third-party software
Fluendo MP3 plugin includes MPEG Layer-3 audio decoding technology licensed from Fraunhofer IIS and Technicolor SA.
Quit
Back
Continue
Right Ctrl

Keep default installation and “install now” and confirm with “continue” on the pop up



Then choose time zone and login details

Then wait for file copy and Ubuntu installation restart the machine after it is complete

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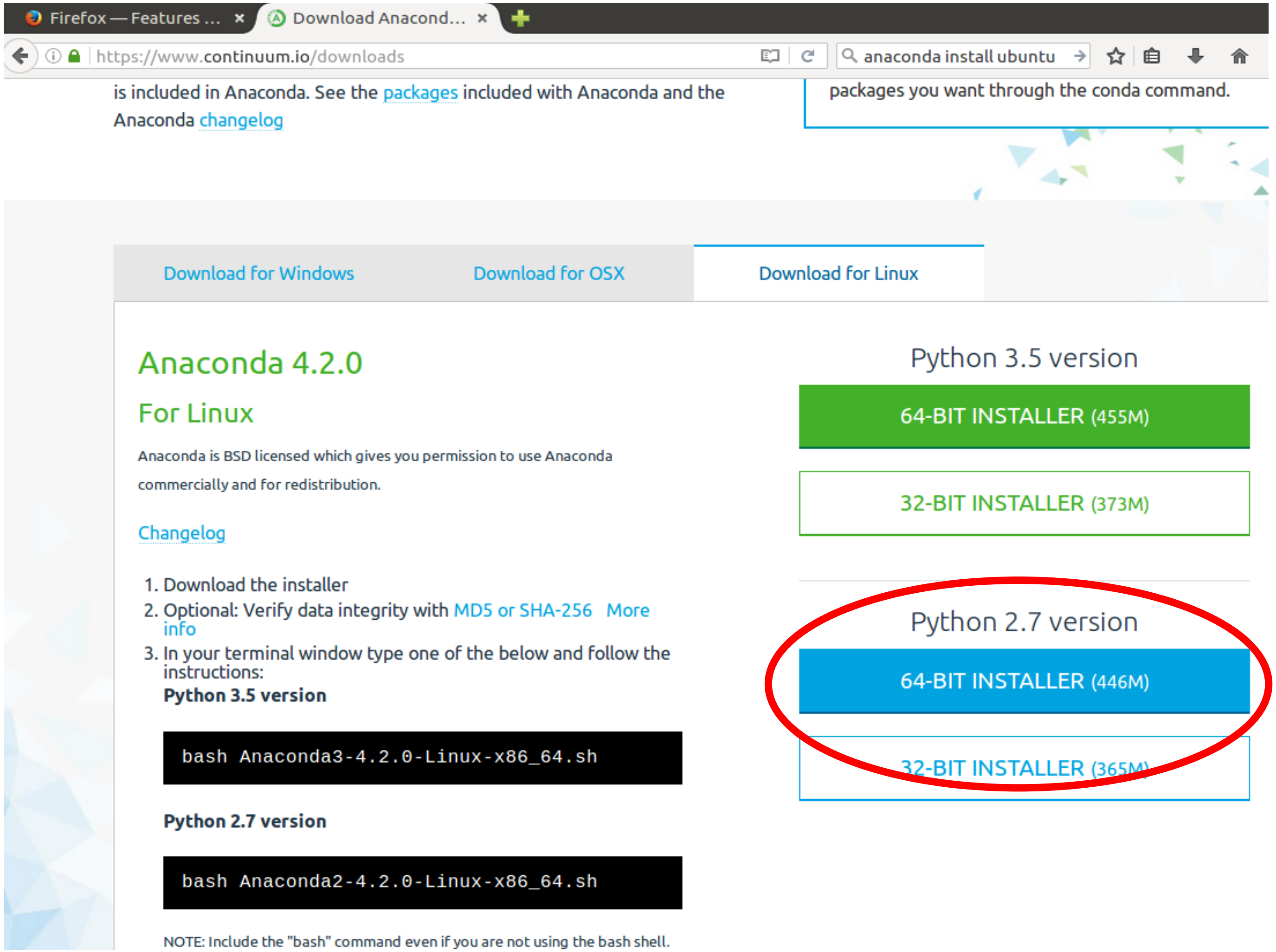
Install anaconda

Go to https://www.continuum.io/downloads and follow instructions



Do not forget to add Anaconda to path (answer yes or add the path yourself in the “.bashrc” configuration file)

```
Python 2.7.12 :: Continuum Analytics, Inc.
creating default environment...
installation finished.
Do you wish the installer to prepend the Anaconda2 install location
to PATH in your /home/juas/.bashrc ? [yes|no]
[no] >>>
You may wish to edit your .bashrc or prepend the Anaconda2 install location:

$ export PATH=/home/juas/anaconda2/bin:$PATH

Thank you for installing Anaconda2!
```

→ Restart the shell (“>>source .bashrc” from the home directory)
→ Check that “>>ipython notebook” works

→ Anaconda contains Python and all the necessary libraries to run PyHEADTAIL.

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Installing PyHEADTAIL

- website for installation and information: https://github.com/PyCOMPLETE/PyHEADTAIL

```
juas@juas-VirtualBox:~/Downloads$ sudo apt install git
```

```
juas@juas-VirtualBox:~/Downloads$ git clone https://github.com/PyCOMPLETE/PyHEADTAIL
```

```
juas@juas-VirtualBox:~$ cd PyHEADTAIL/
```

```
juas@juas-VirtualBox:~/PyHEADTAIL$ make
```

Add path to the end of the .bashrc to be able to import PyHeadtail from everywhere:

```
juas@juas-VirtualBox:~$ gedit ~/.bashrc
```

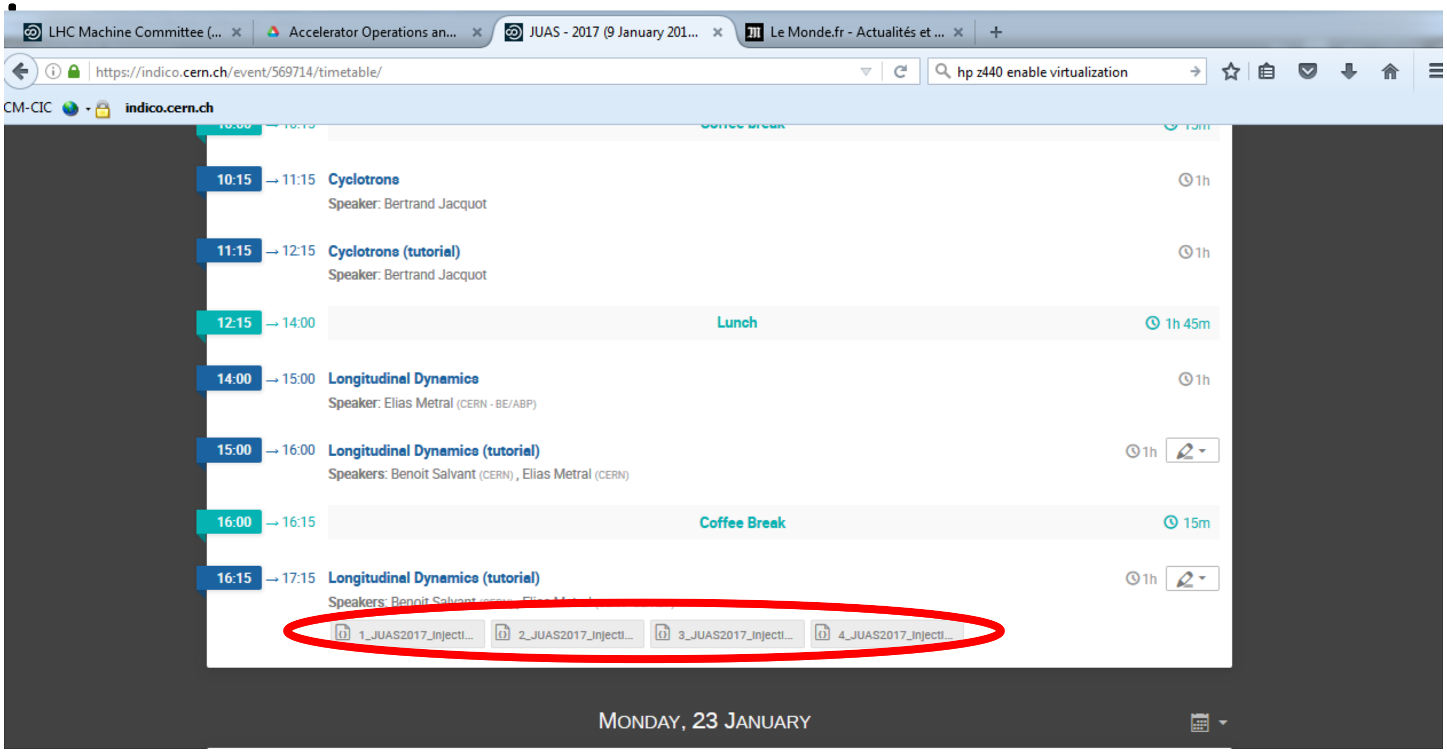
```
# Anaconda
export PATH=/home/juas/anaconda2/bin:$PATH

# PyHEADTAIL
export PYTHONPATH=/home/juas/:$PYTHONPATH
```

This only updates once a new terminal is opened (or do source ~/.bashrc)

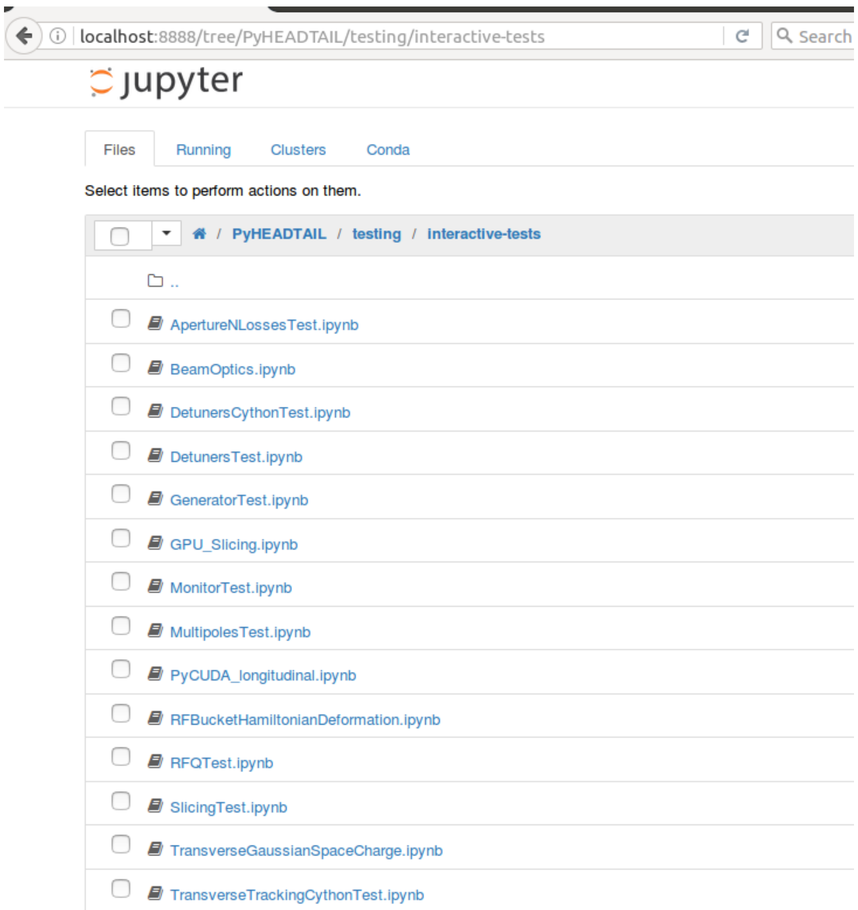
Finding the examples

- From JUAS Indico site in the last tutorial of the course:



→ Download the files and open them browsing with "ipython notebook"

Other examples available with the PyHEADTAIL install



Other interesting examples to run

- Doublet beam creation
- PS to SPS transfer
- Double and triple splitting

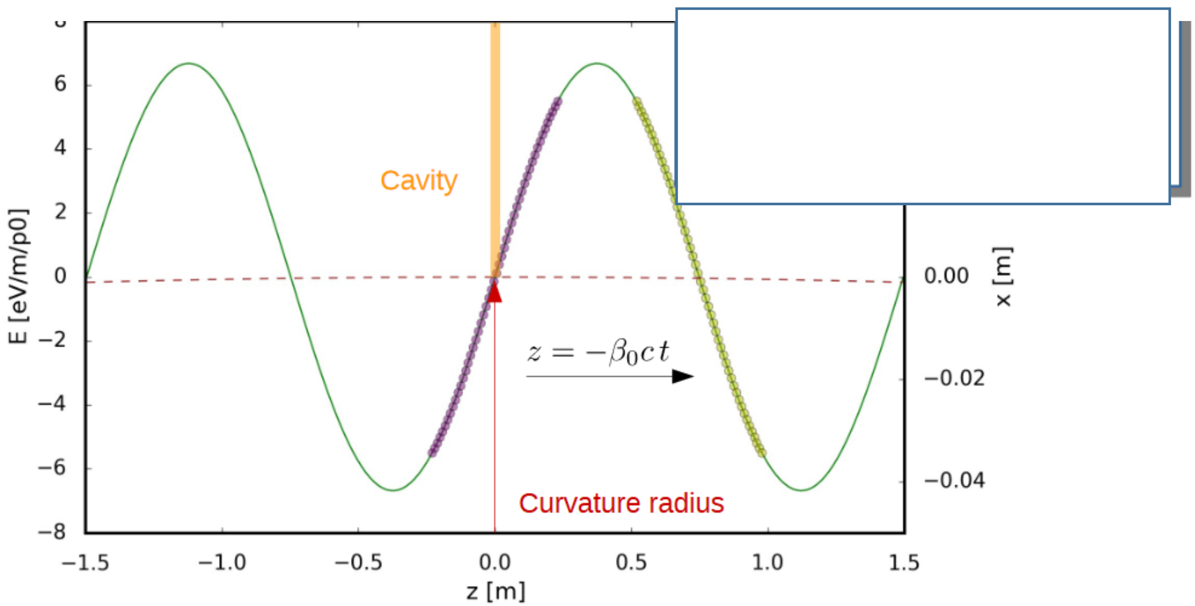
Changing variables

- Change of variables if one wants to use (Φ, ΔE) or (Δt, ΔE) instead of (Φ, $d\Phi/dt$)

$$\Delta\phi = \phi - \phi_s = \omega_{RF}\,\Delta t = h\,\omega_s\,\Delta t$$

$$\Delta p = \frac{\Delta E}{\beta_s\, c}$$

$$\dot{\phi} = -\frac{\eta\, h\, c}{\beta_s\, E_s\, R_s}\,\Delta E$$



$$\Delta\phi[rad] = -\frac{h}{R}\, z[m]$$

$$\Delta \mathrm{E} = \frac{\Delta p}{p} m_0 \gamma \beta^2 c^2$$

For protons $\Delta \mathrm{E}[GeV] = \dfrac{\Delta p}{p} 0.938\, \gamma\beta^2$