PyHEADTAIL examples

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

and

Martial Fol and Saïd Errghioui (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

- 1h00 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)

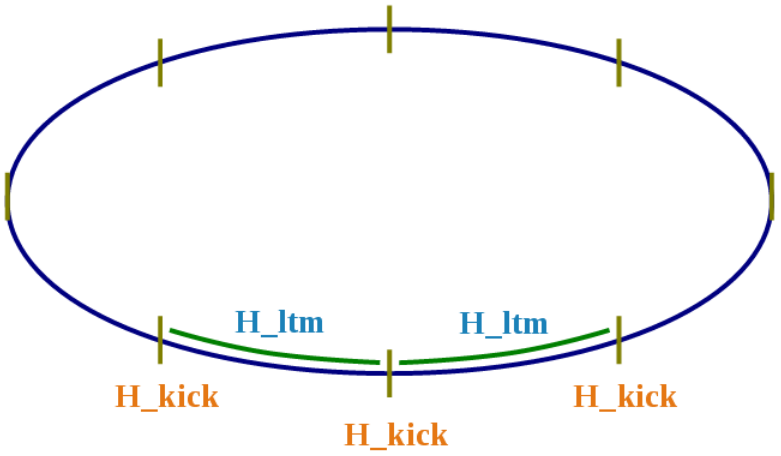
- Not the only code of his kind!
  - BLOND: longitudinal dynamics simulation code https://blond.web.cern.ch/
  - HEADTAIL: the father of PyHEADTAIL! G. Rumolo et al (reference)
  - elegant: 6D tracking code developed at Argonne National Lab (link)
  - mbtrack and sbtrack: R. Nagaoka et al "Studies of 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

How does PyHEADTAIL work?

- PyHEADTAIL is a macroparticle tracking code designed specifically to simulate collective effects in circular accelerators



- H_ltm: linear transfer map
  - Chromaticity
  - Amplitude detuning
  - …
- H_kick: collective interaction
  - Wakefields
  - Electron cloud
  - Feedback
  - Space-charge
  - …

introduction to PyHEADTAIL

A real world example

Courtesy
Kevin Li
USPAS 2015

- Load Python packages and modules

```
1  from __future__ import division
2  import cProfile, itertools, sys, time, timeit
3
4  from scipy.constants import c, e, m_p
5
6  from cobra_functions import stats, random
7  from beams.beams import *
8  from monitors.monitors import *
9  from spacecharge.spacecharge import *
10 from trackers.transverse_tracker import *
11 from trackers.longitudinal_tracker import *
12
```

introduction to PyHEADTAIL

A real world example

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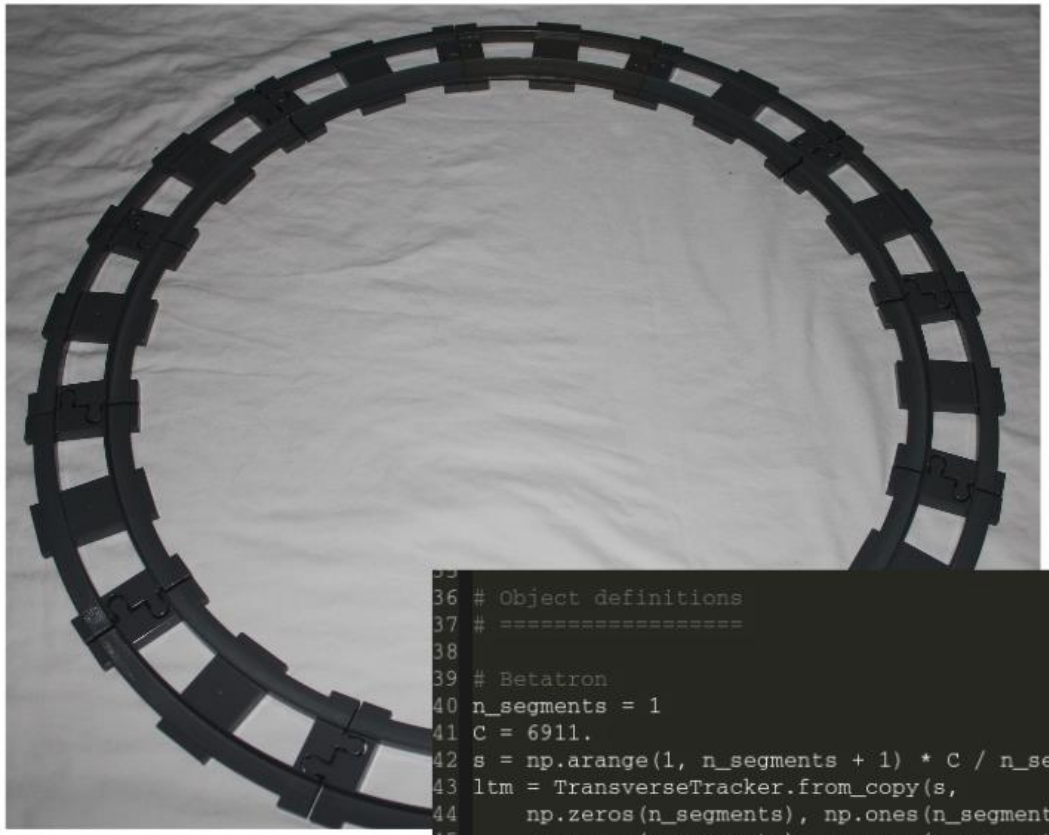
USPAS 2015



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

```
# 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)
```

A real world example

Courtesy
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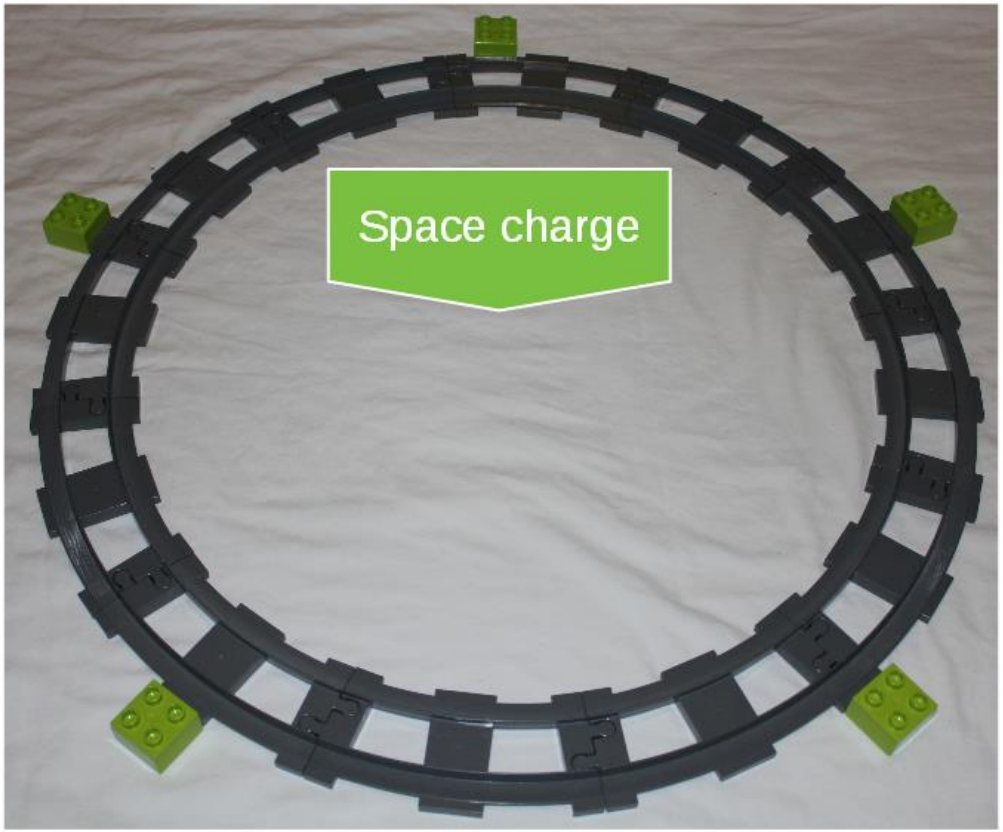
USPAS 2015



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

A real world example

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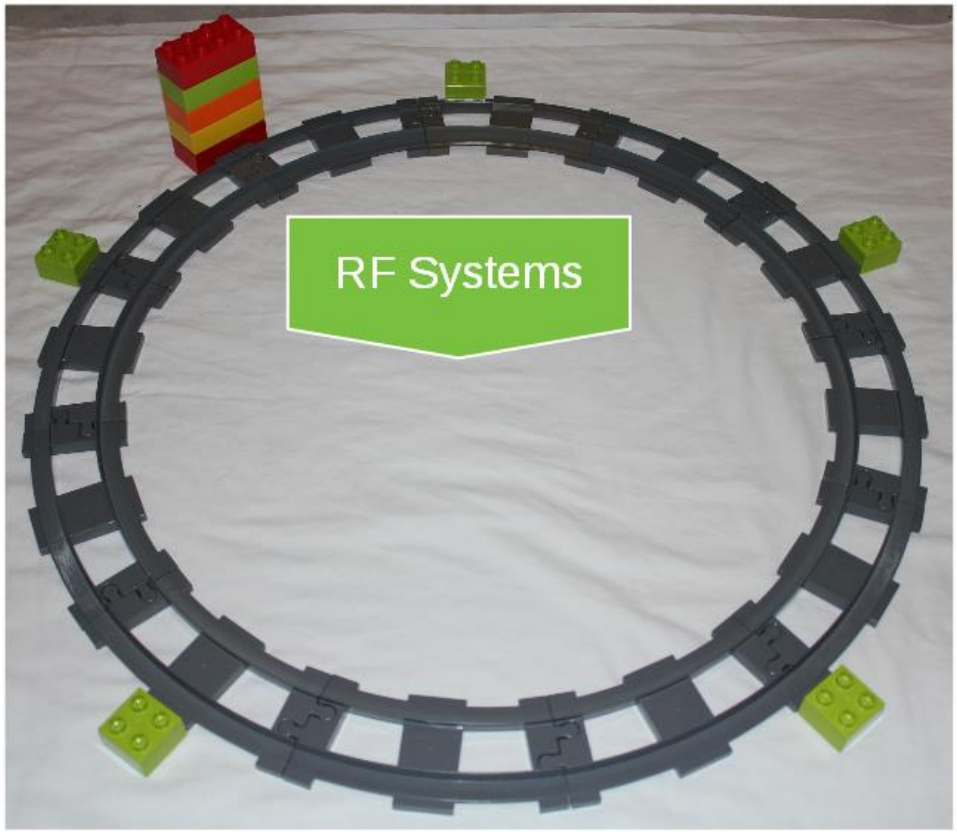

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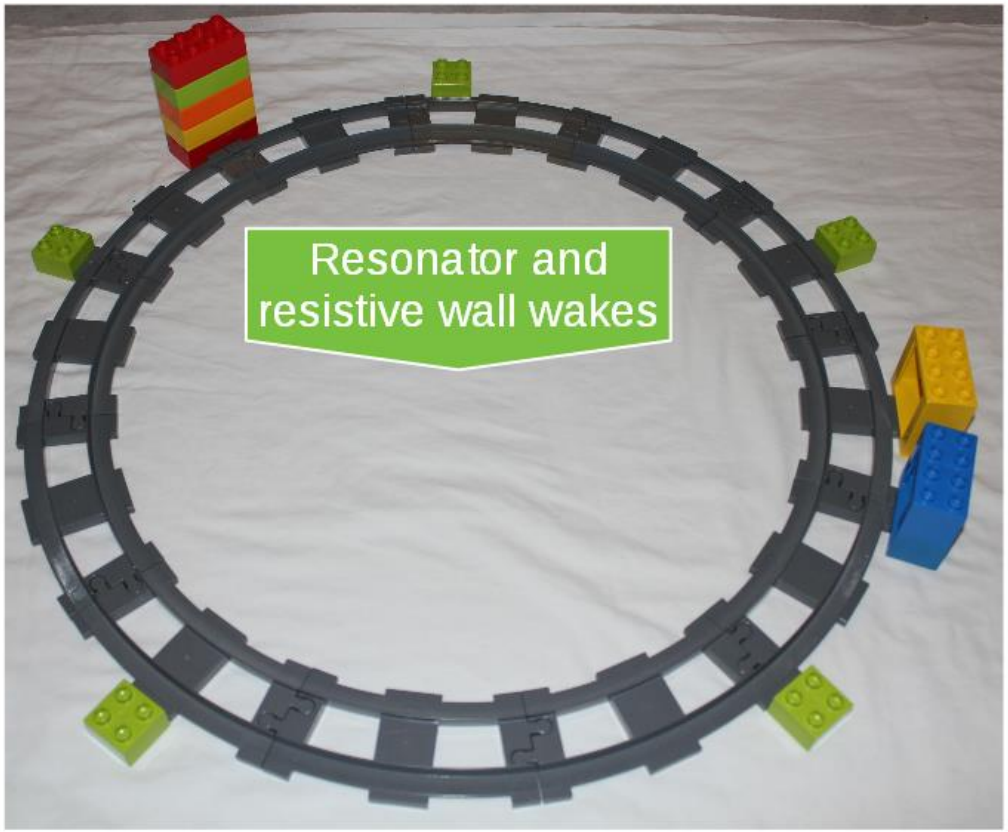

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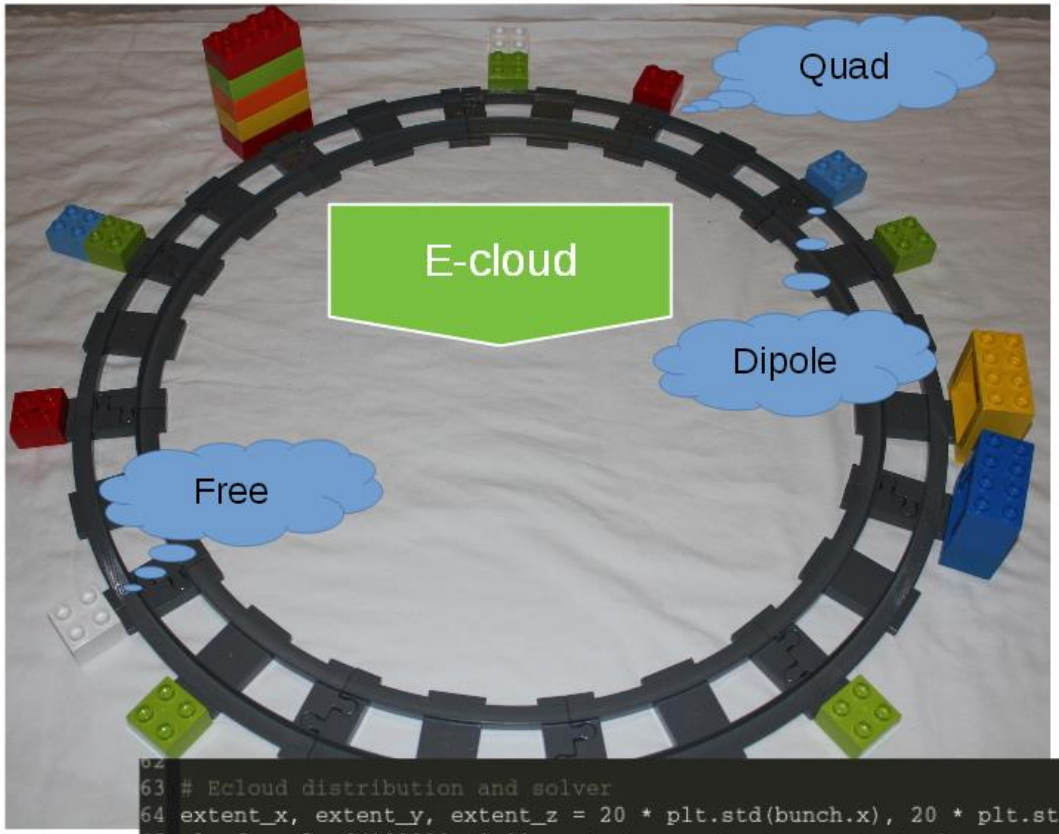

- Load Python packages and modules
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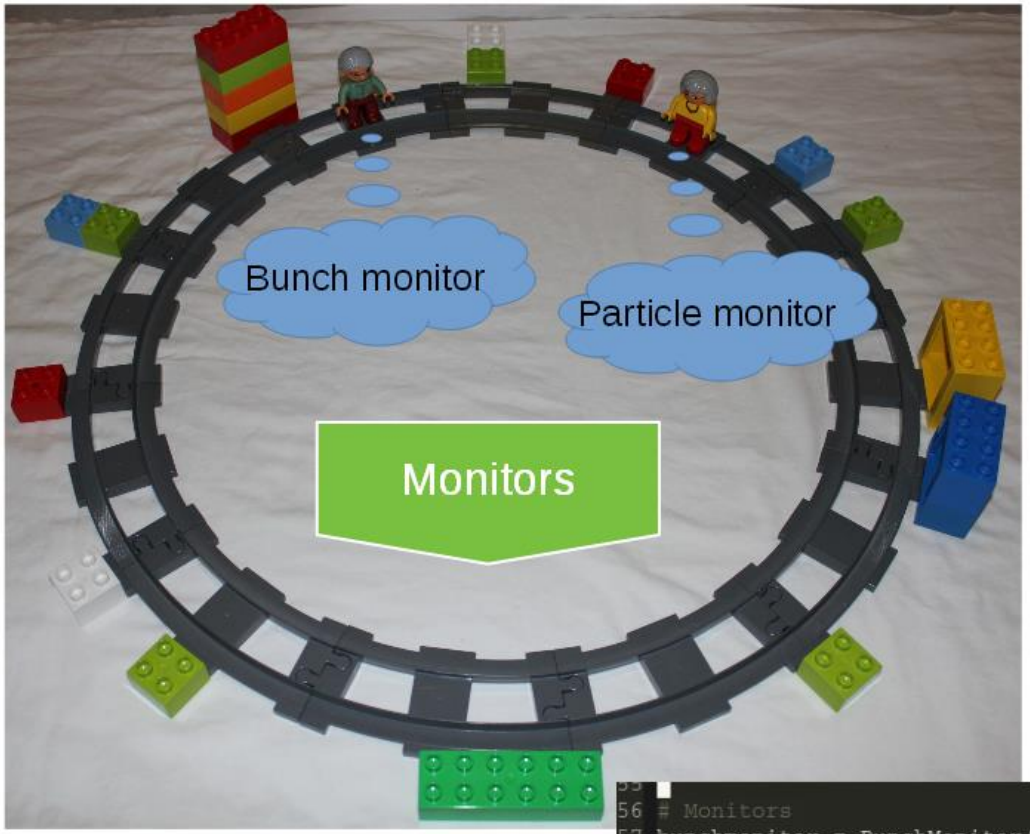
```
63 # Ecloud distribution and solver
64 extent_x, extent_y, extent_z = 20 * plt.std(bunch.x), 20 * plt.std(bunch.y), C / n_segments
65 cloud = Cloud(100000, 1e11, extent_x, extent_y, extent_z)
66 ecloud = SpaceCharge(cloud, 'cloud', extent_x, extent_y, 128, 128, slices)
67
```

A real world example

Courtesy
Kevin Li
USPAS 2015

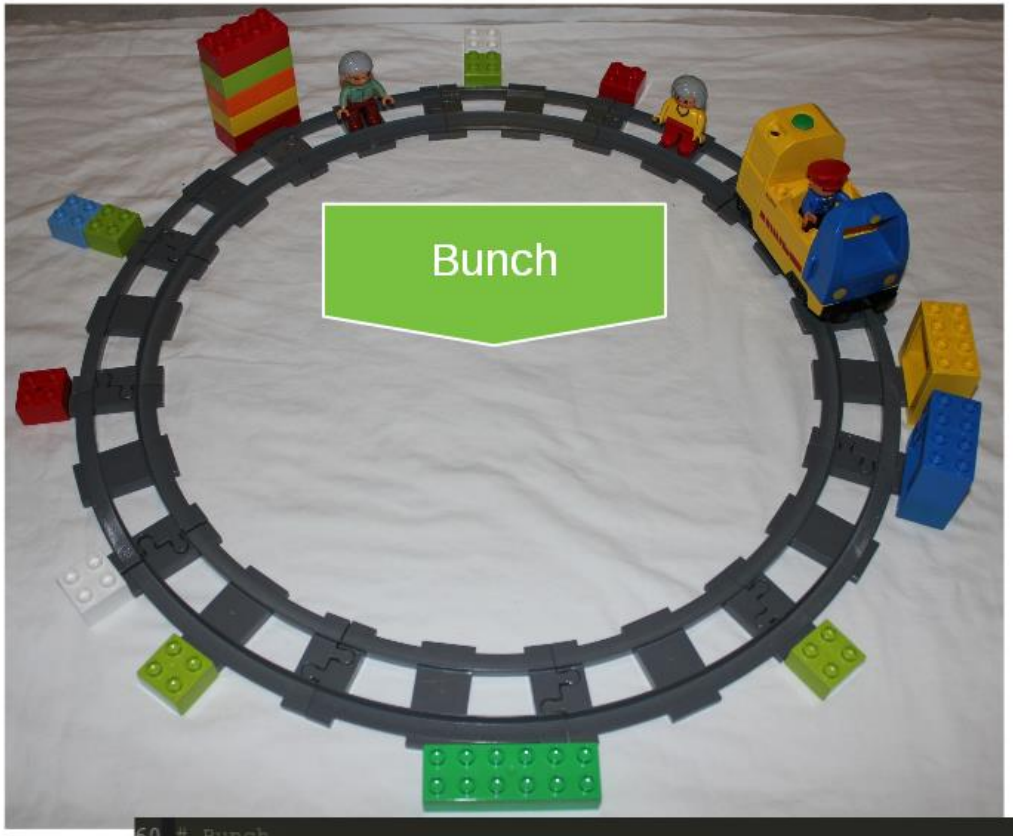


- Load Python packages and modules
- Build linear periodic transfer maps
- Add (collective) kick elements

```
# Monitors
bunchmonitor = BunchMonitor('bunch', n_turns, slices)
particlemonitor = ParticleMonitor('particles', n_turns, slices)
```

A real world example

Courtesy
Kevin Li
USPAS 2015



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

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

A real world example

Courtesy
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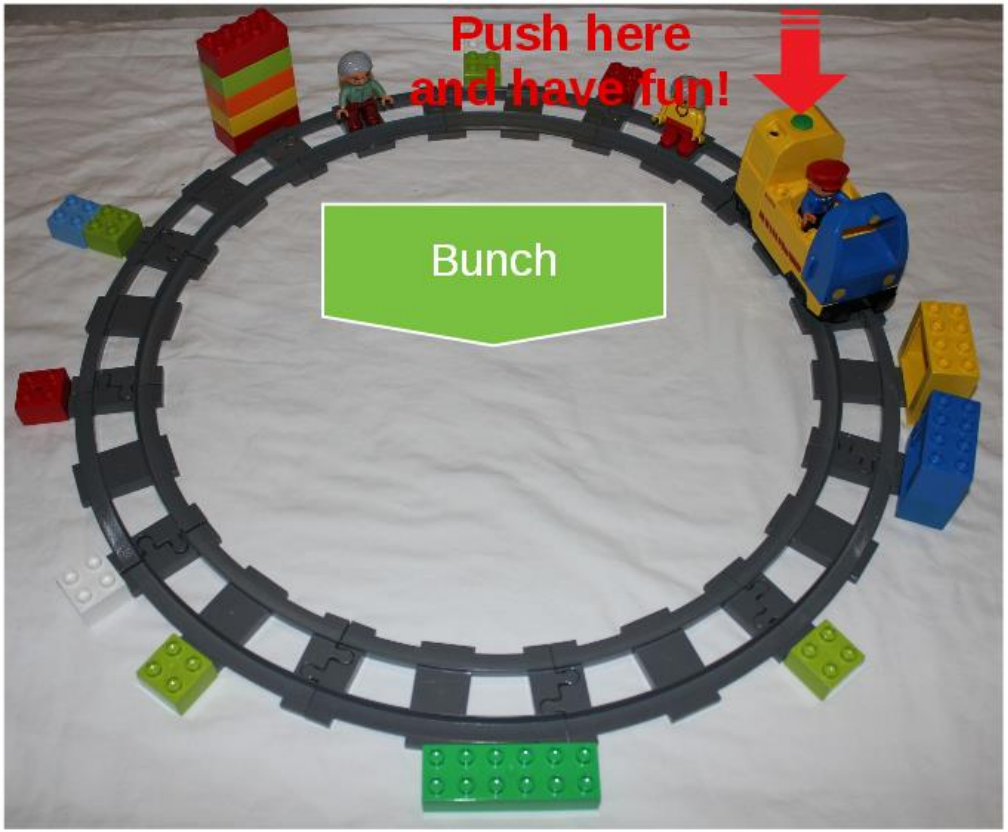
USPAS 2015



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

```
86 for i in range(n_turns):
87     for m in map_:
88         m.track(bunch)
89
```

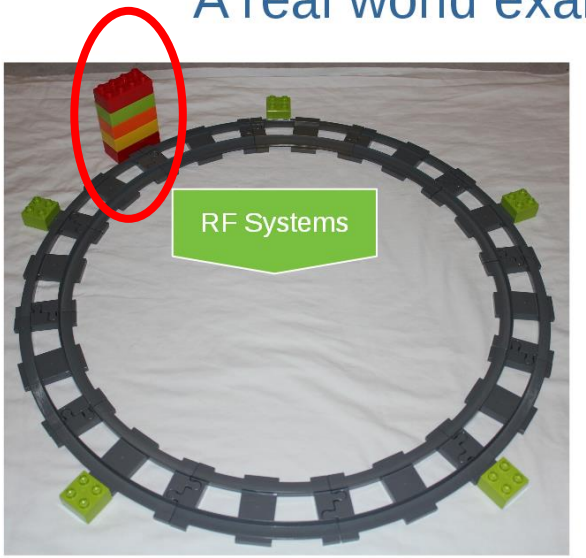
In our case: only RF systems

- 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

```
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 system

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

Generate a matched distribution corresponding to these parameters

```
# 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

```
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()
```

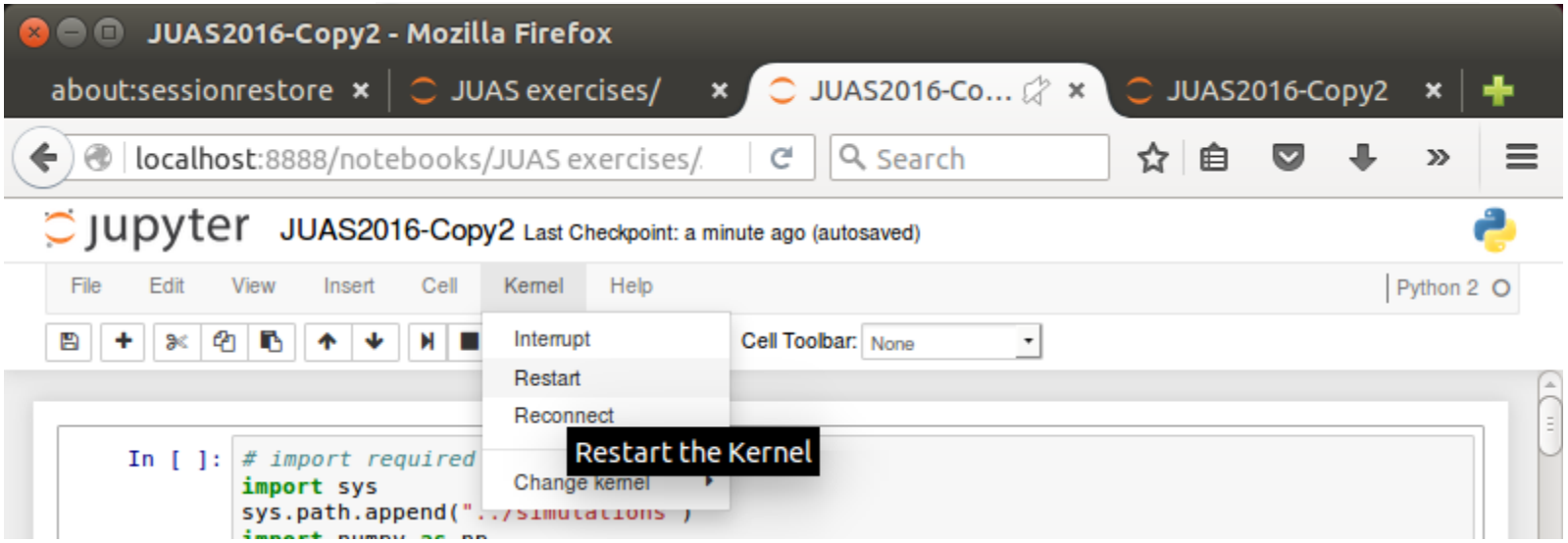
track

monitor

plot

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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```
Ekin = 1.4e9 # in [eV]
```

```
circumference = 100*2*np.pi
```

```
bending_radius=70 # in m
```

```
Bdot=0 # in T/s
```

20 kV at injection

```
V_rf = 20e3 # in [V]
```

```
harmonic = 8
```

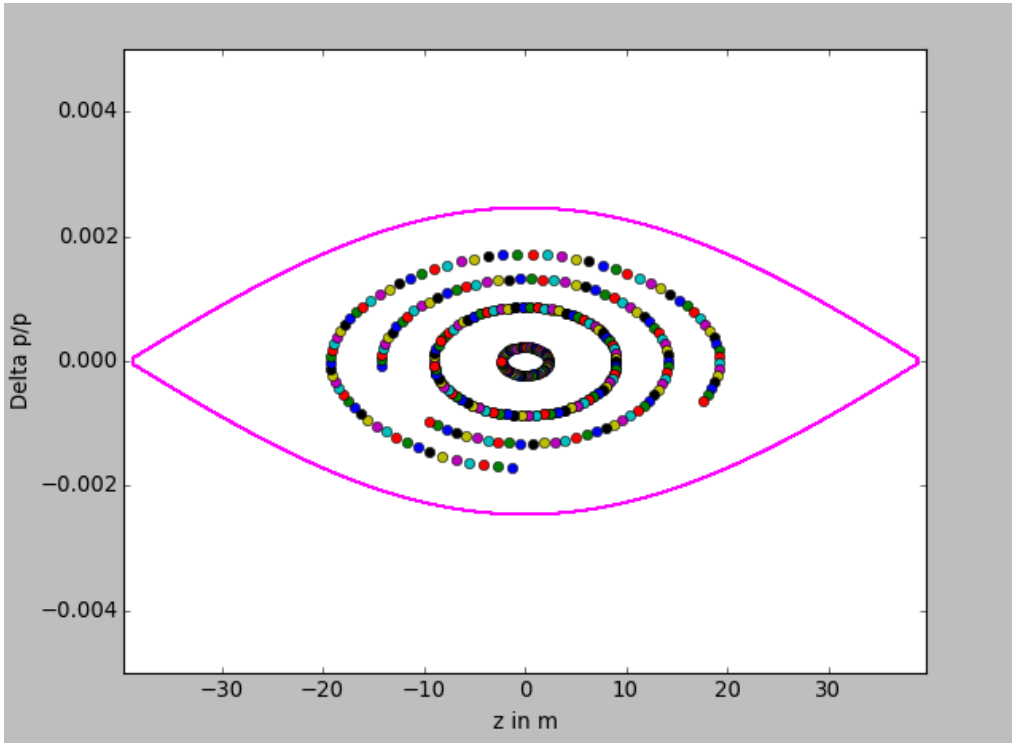
=> $\gamma_t \approx 6.1$

```
gamma_tr = 6.1
```

```
sigma_z_0= 230e-9/4*beta*c
```

Let’s run that example

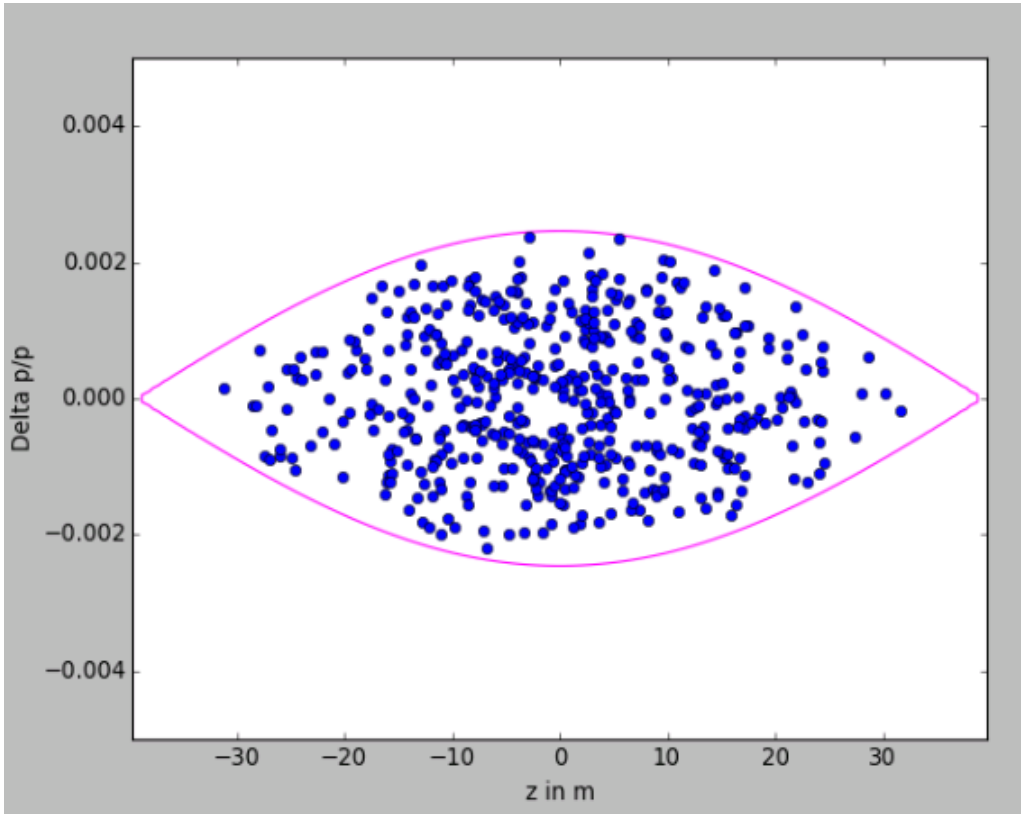
- Use a small number of particles (n_particles~ 10) to observe the synchrotron motion at large and small amplitudes



→ 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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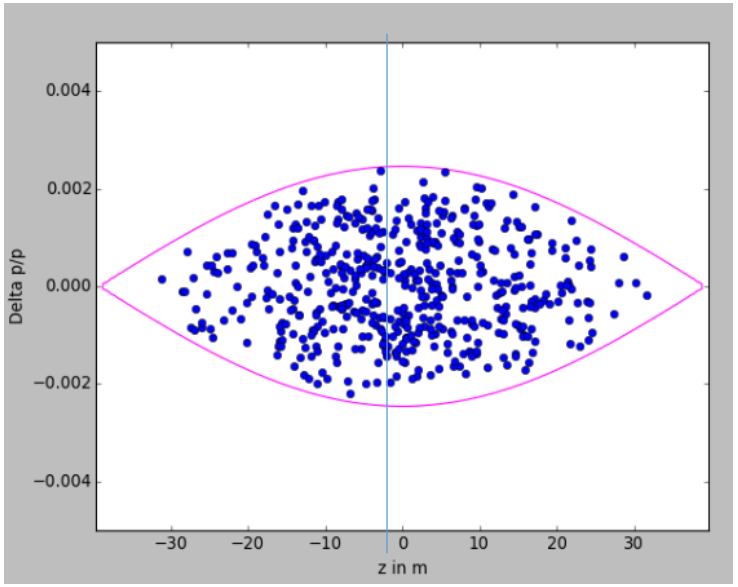
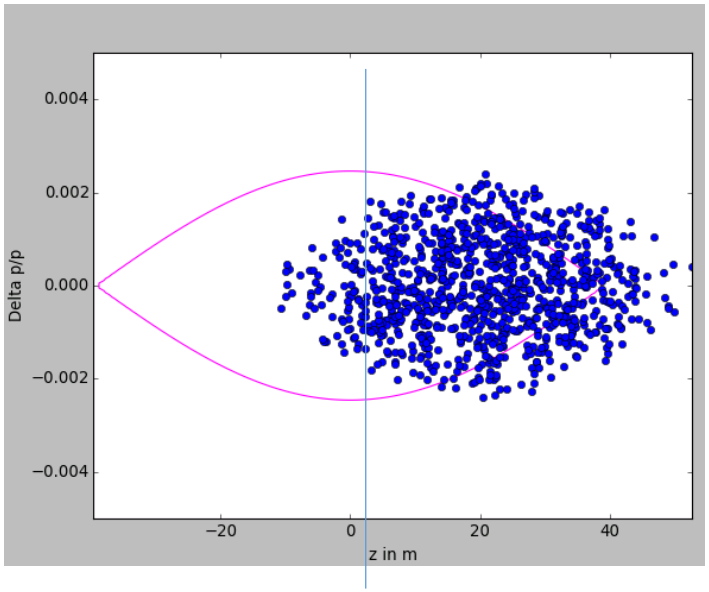
Impact of phase mismatch

- 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:`

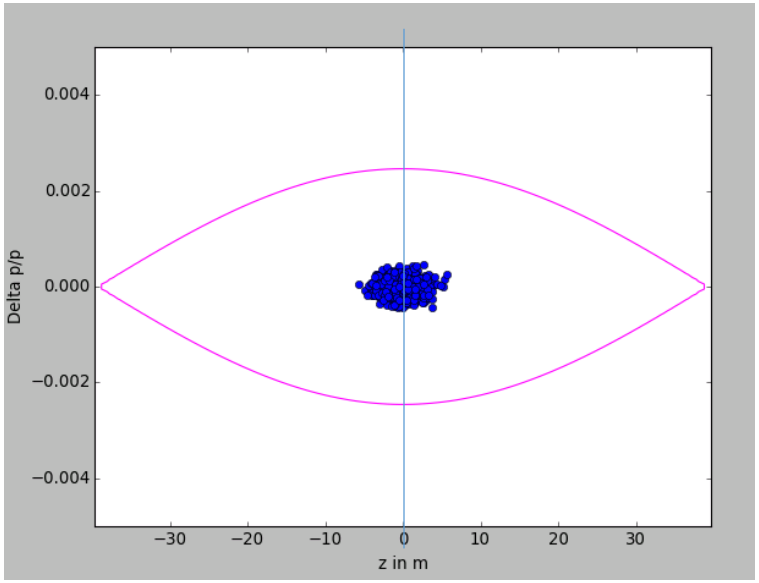


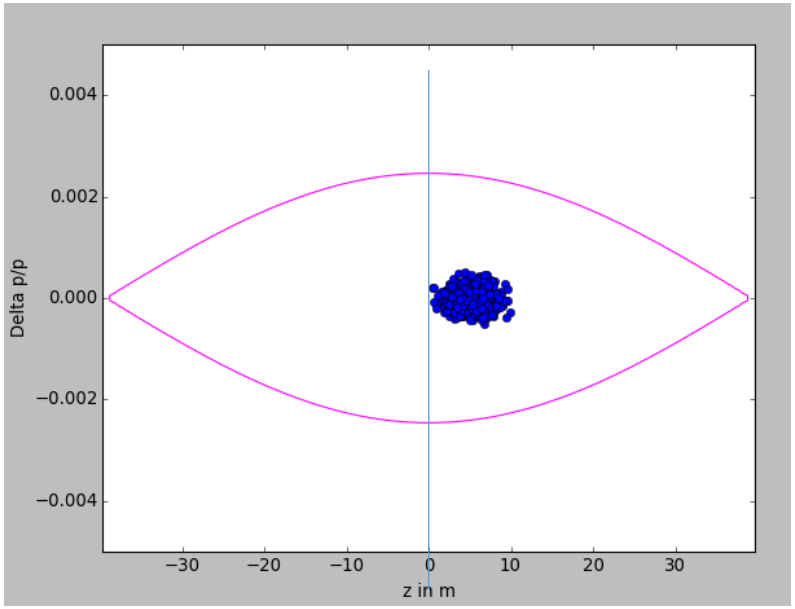


→ What will happen?

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:`





→ What will happen?

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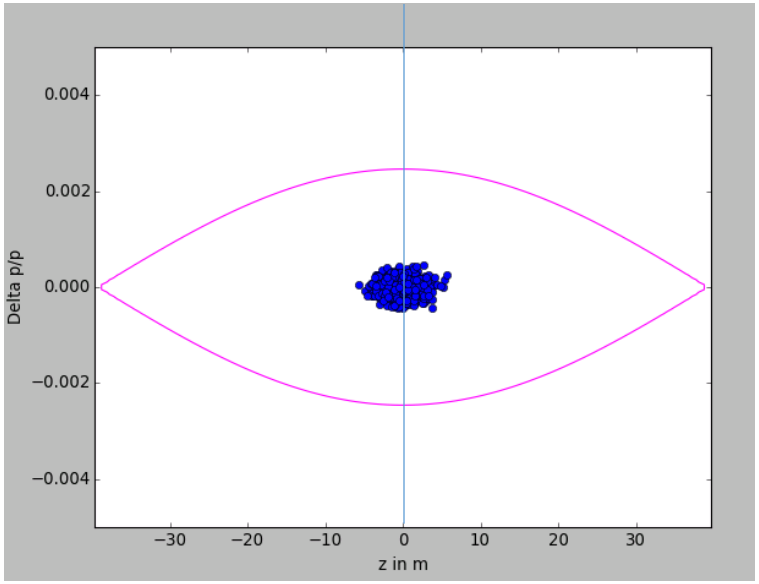
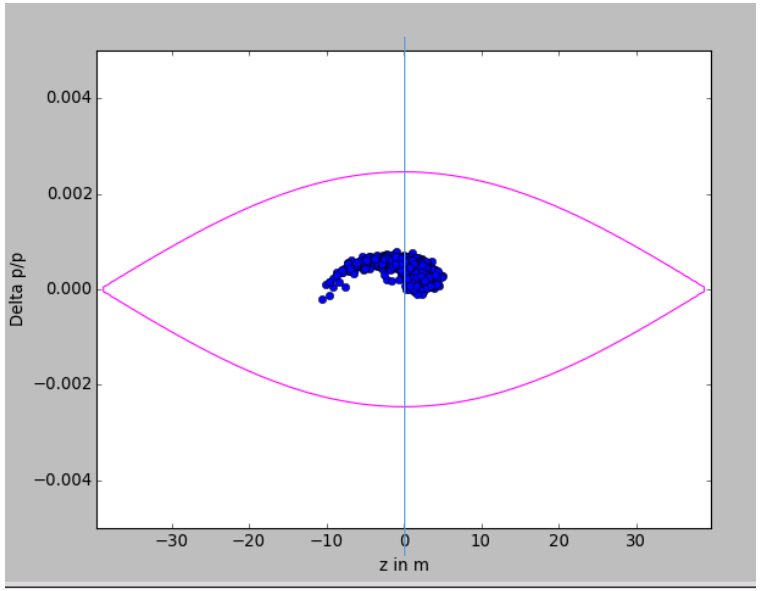
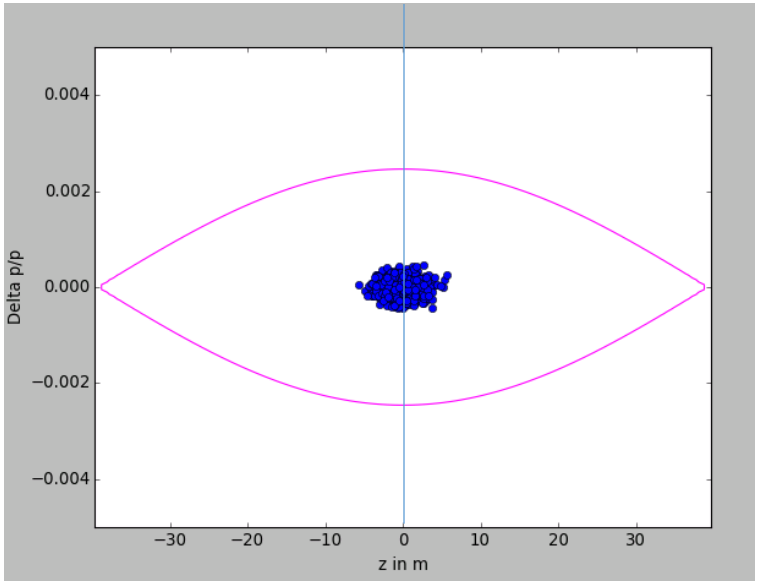


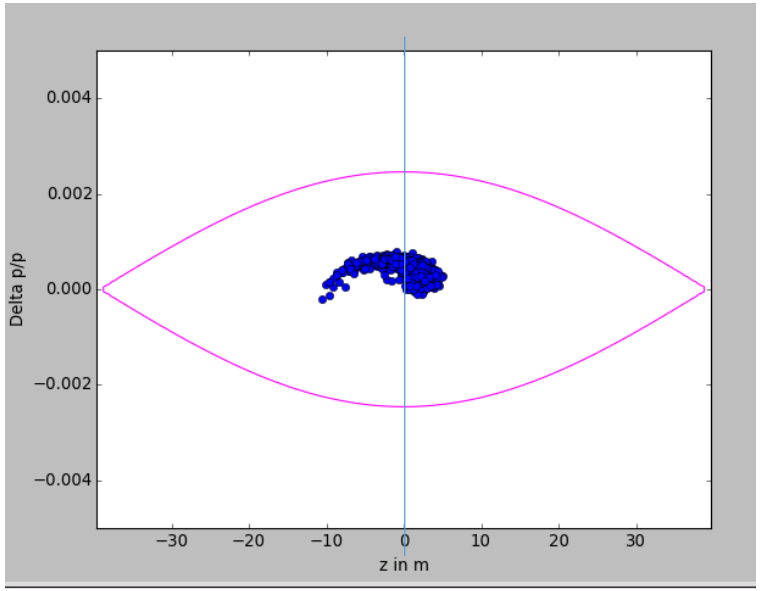


→ Filamentation and eventually?

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

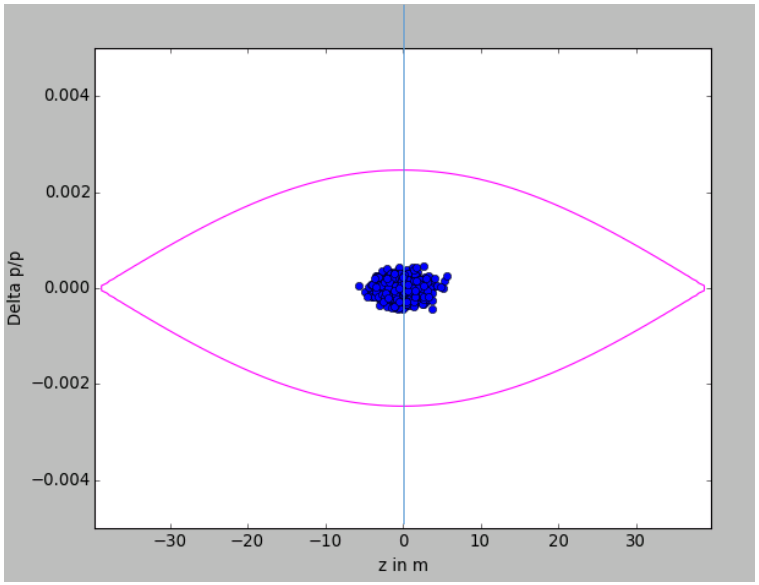


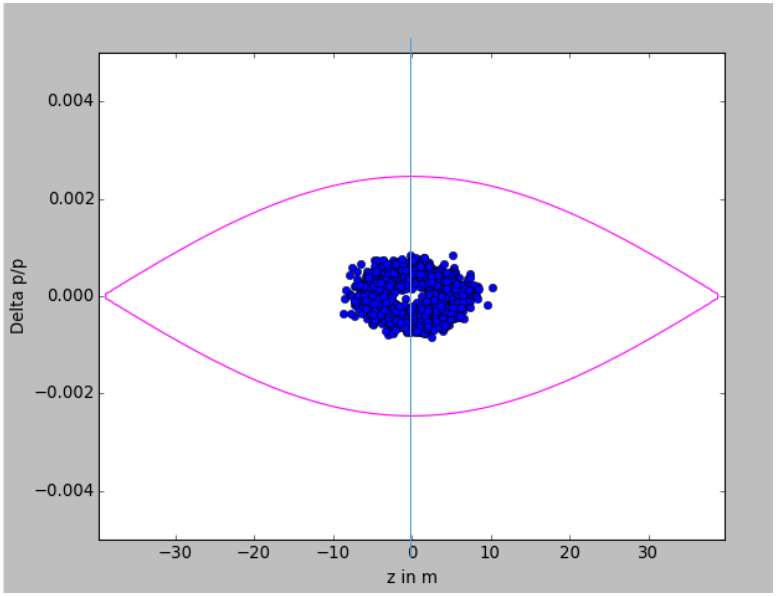


→ Filamentation and eventually?

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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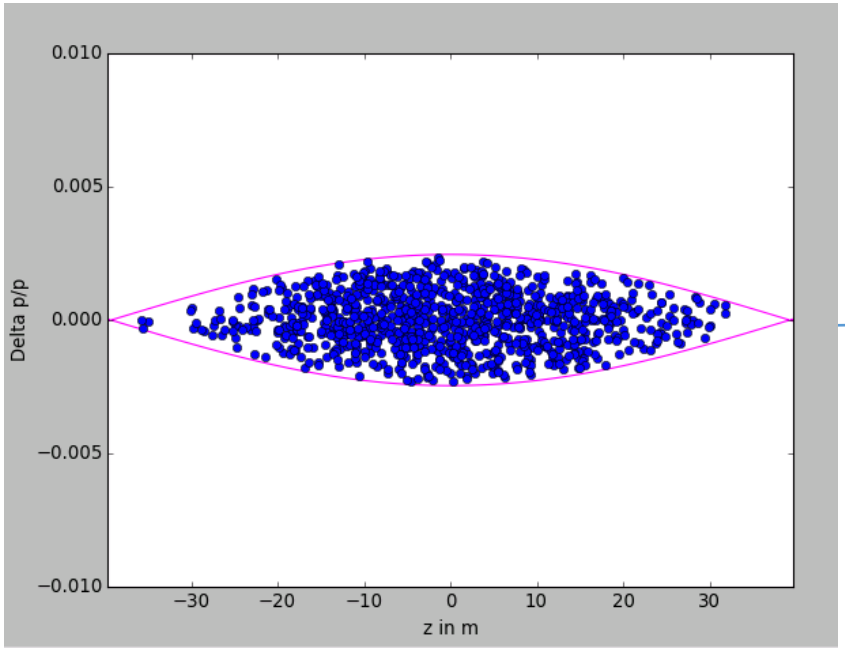
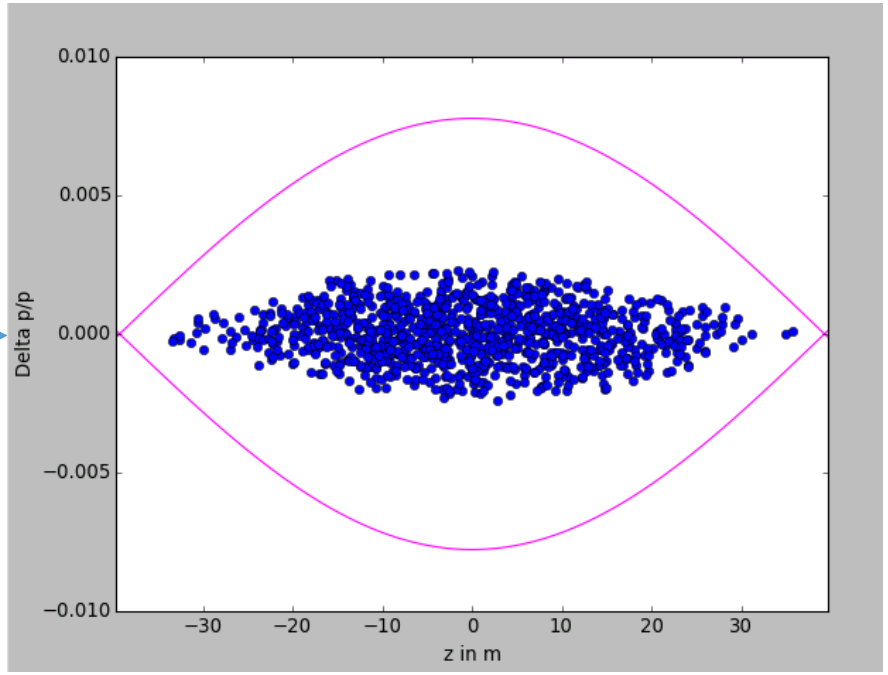
Impact of voltage mismatch (too high)

- 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)
```



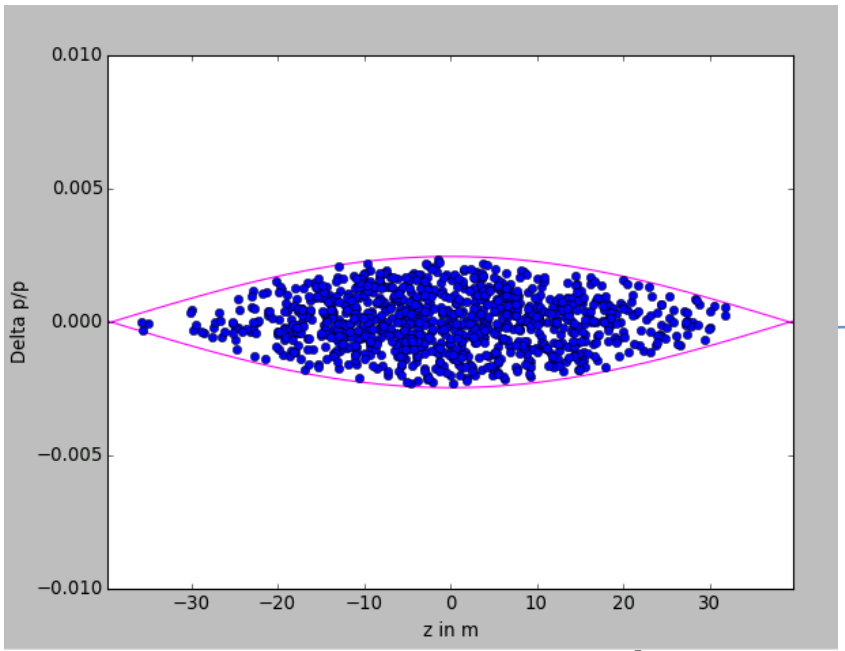


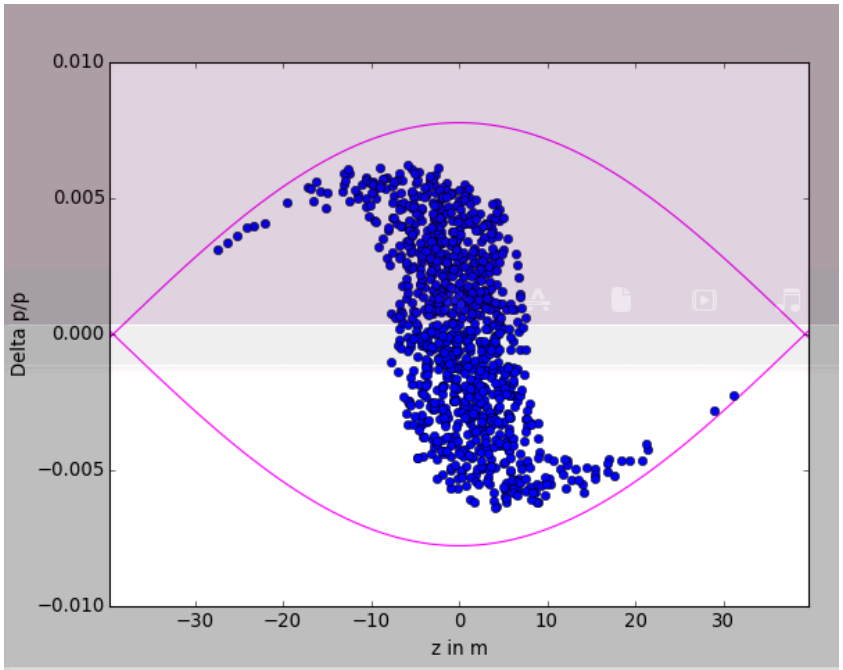
→ What will happen?

Impact of voltage mismatch (too high)

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





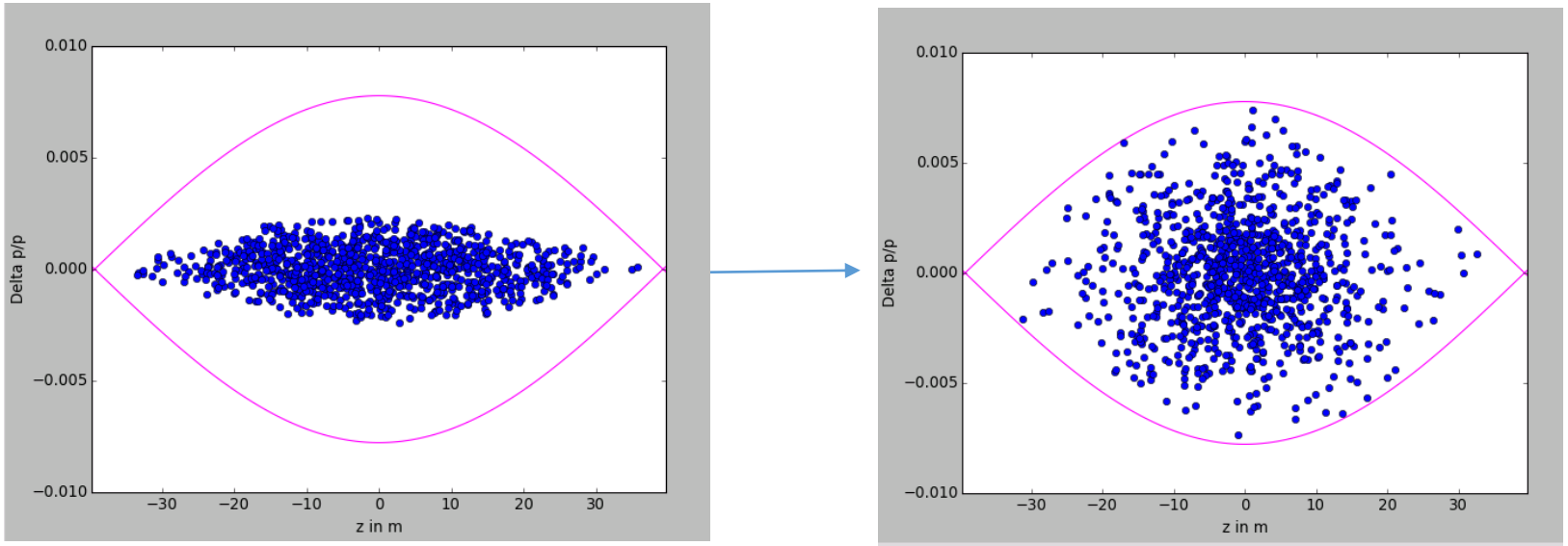
→ Bunch rotation

→ 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)
```

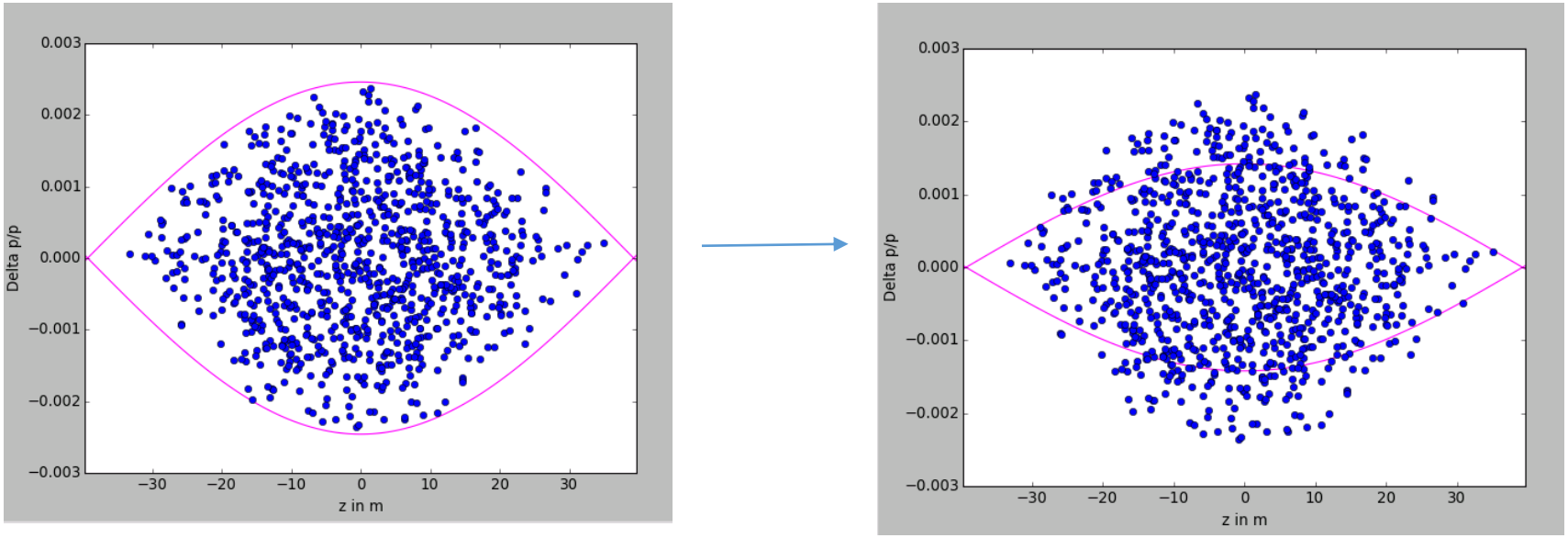


→ But should not wait too long!

→ Emittance growth!

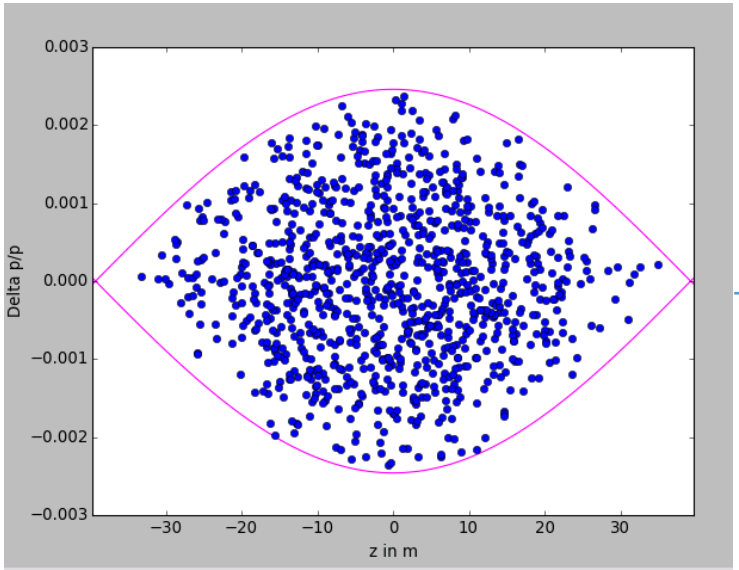
Impact of voltage mismatch (too low)

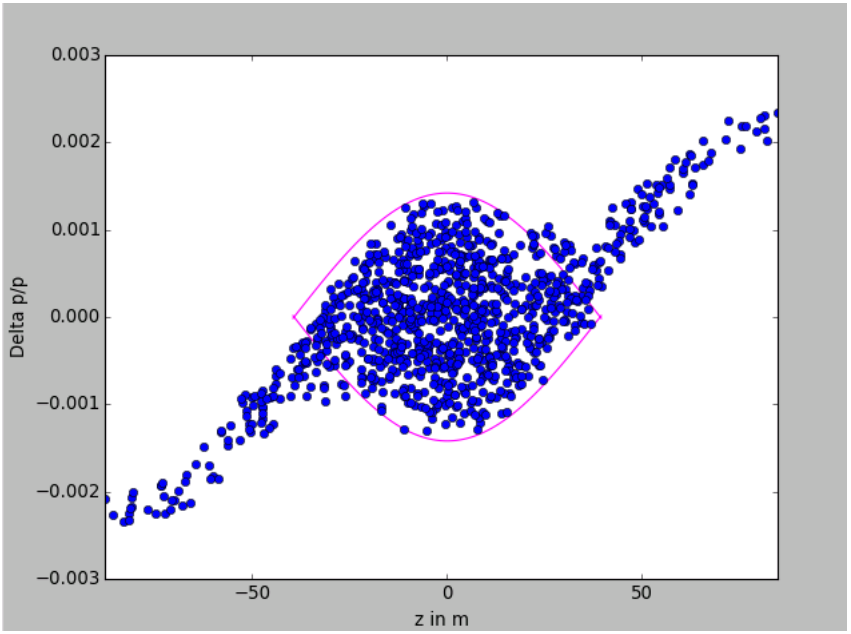
- Use the nominal bunch length
- track 1000 particles for 500 turns (plot every 10 turns)
- Change V_RF to V_RF/10 after the bunch is matched to V_RF
- Adapt the deltap plotting limits



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
- Structure of ipython files
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  - Impact of phase mismatch
  - Impact of voltage mismatch
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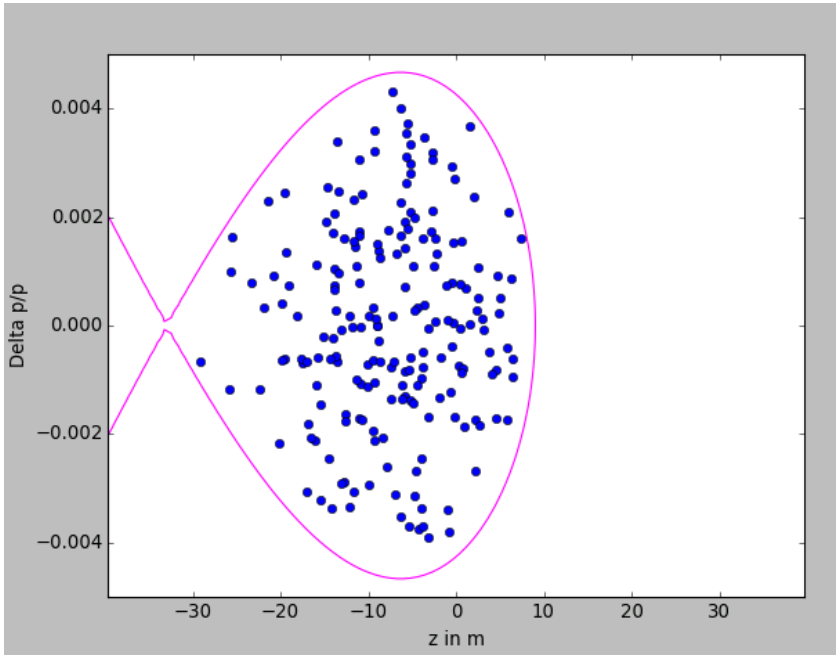
Impact of acceleration

- 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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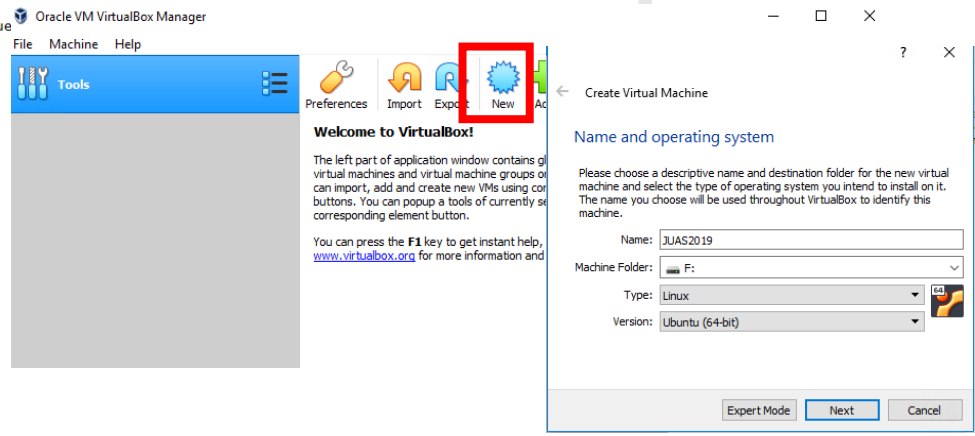
Setting up the operating system

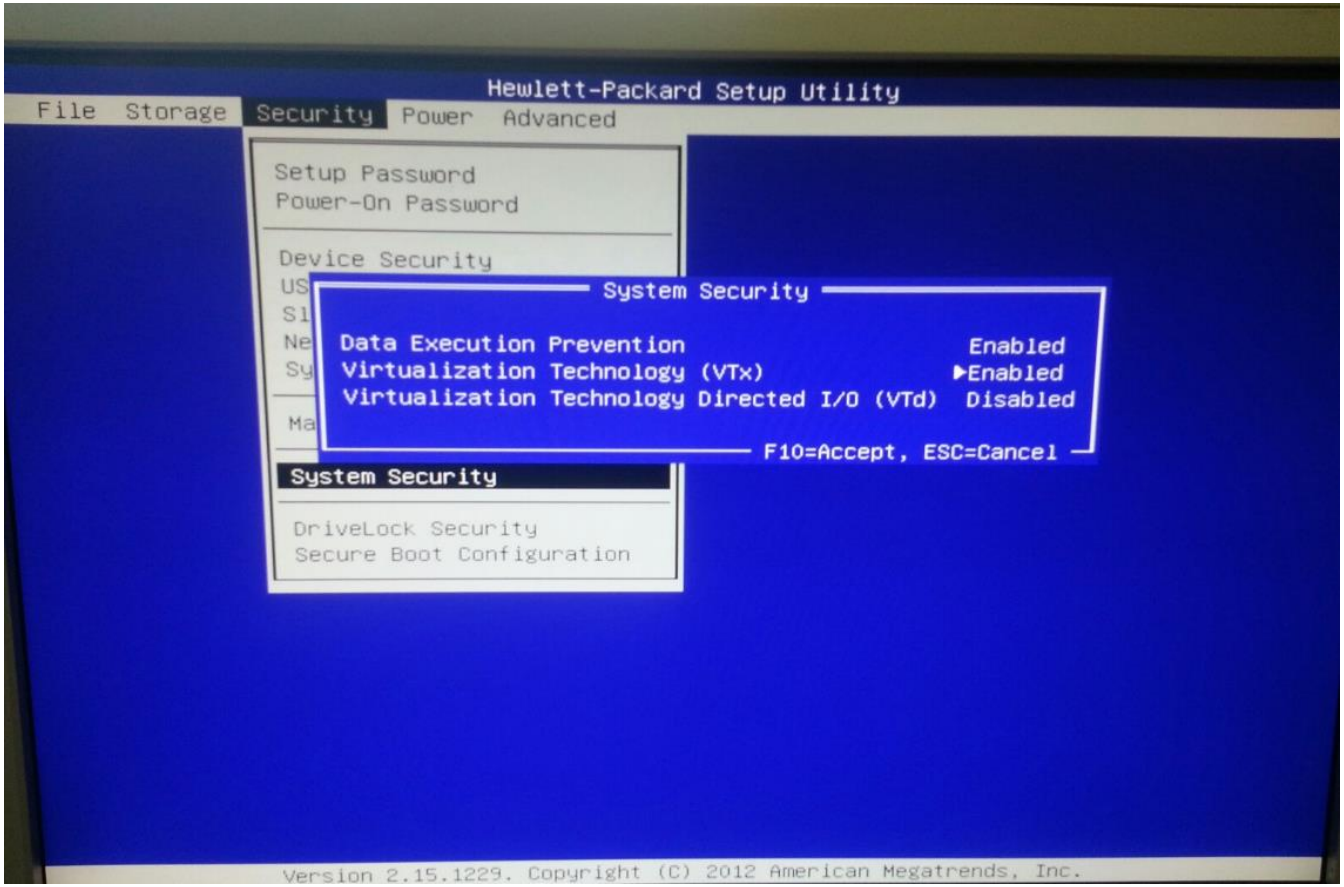
- Install a virtual box to get an Ubuntu environment

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

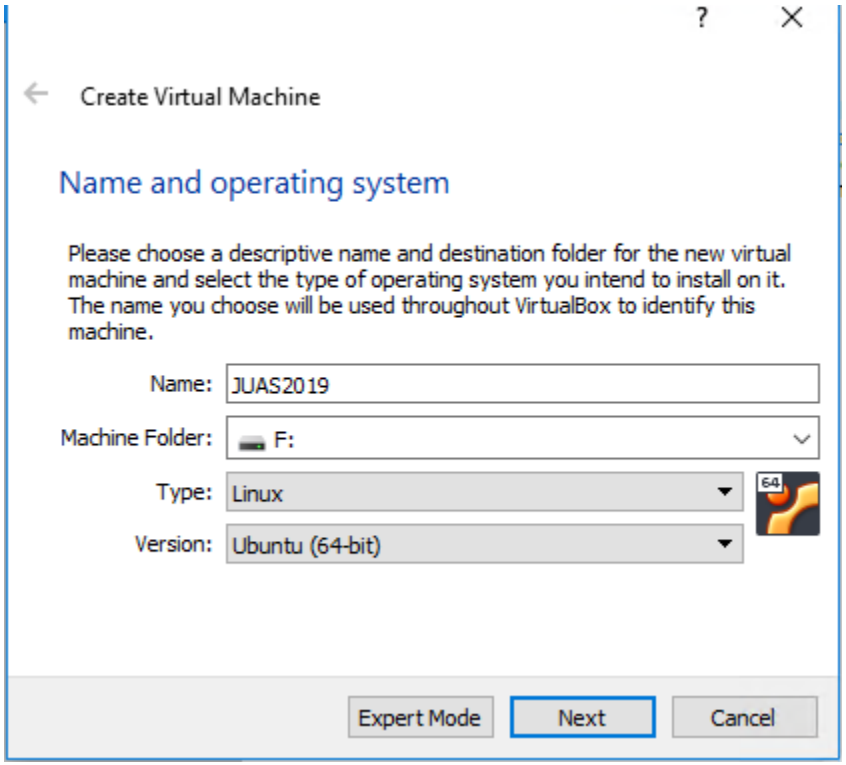
- Create a new virtual machine with Ubuntu 64-bit

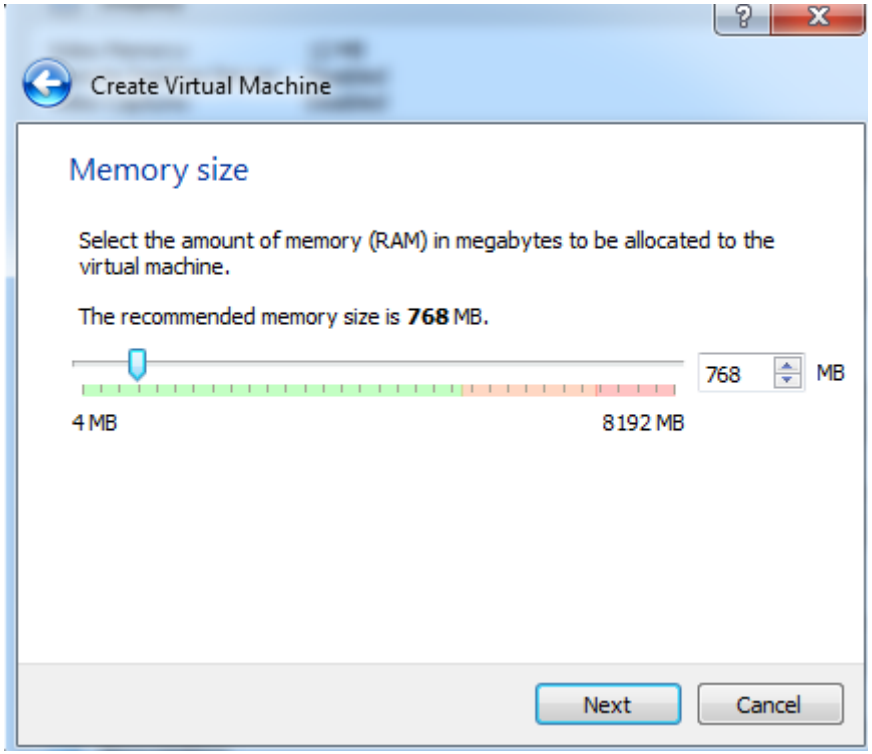


In case of a “VTx” error or an impossibility to select 64 bit operating system when launching the virtual machine, one needs to turn Virtualization Technology (VTx) on in the BIOS (see chapter 10.3 in https://www.virtualbox.org/manual/ch10.html#hwvirt)

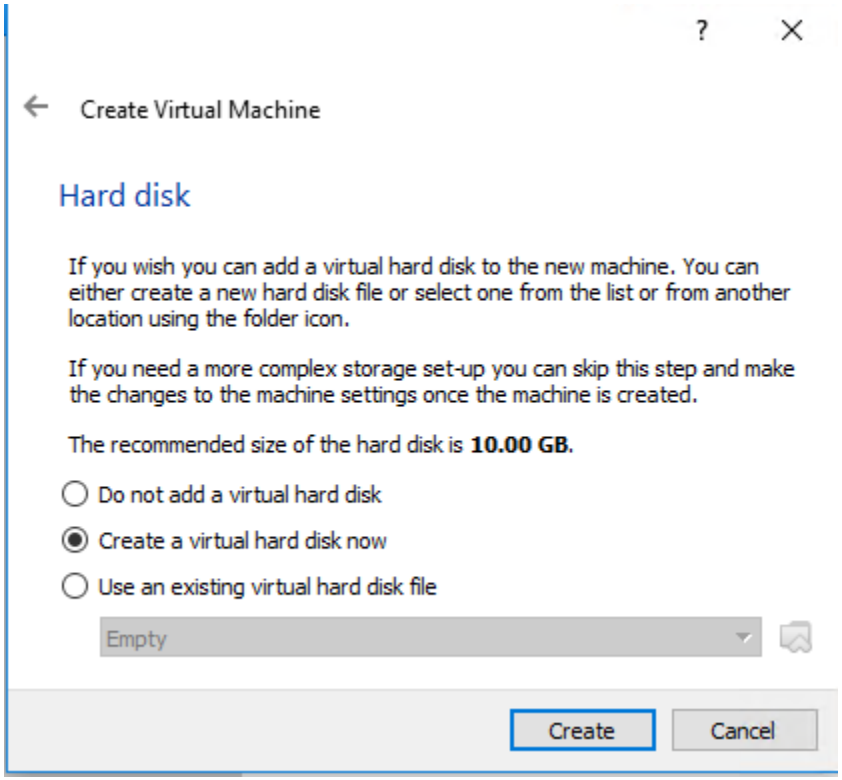


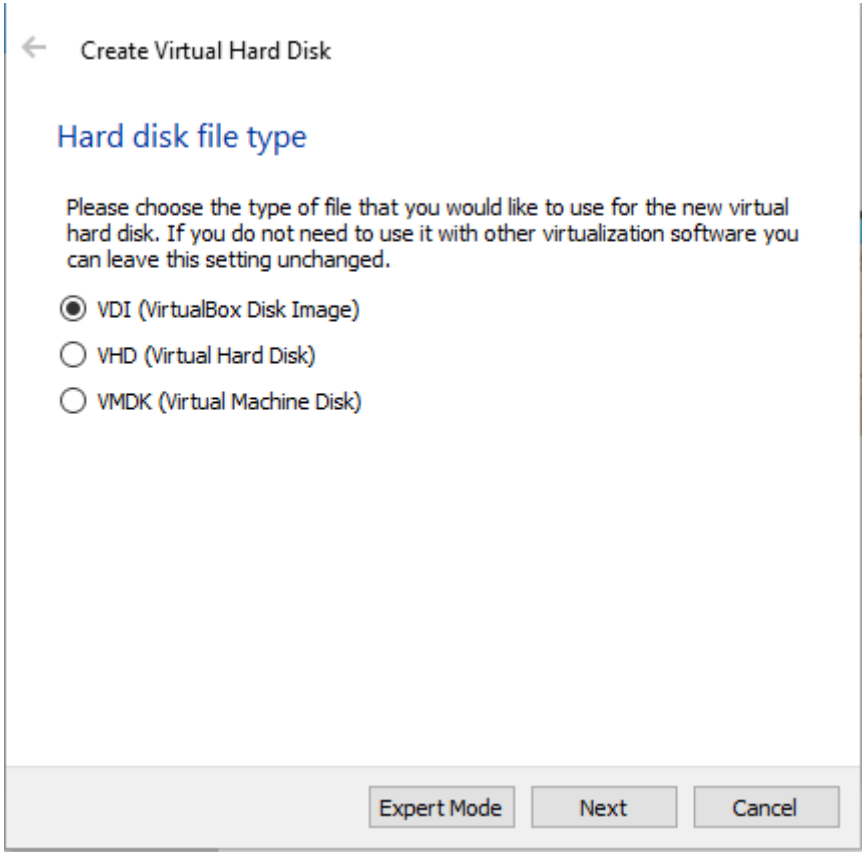
Create virtual machine

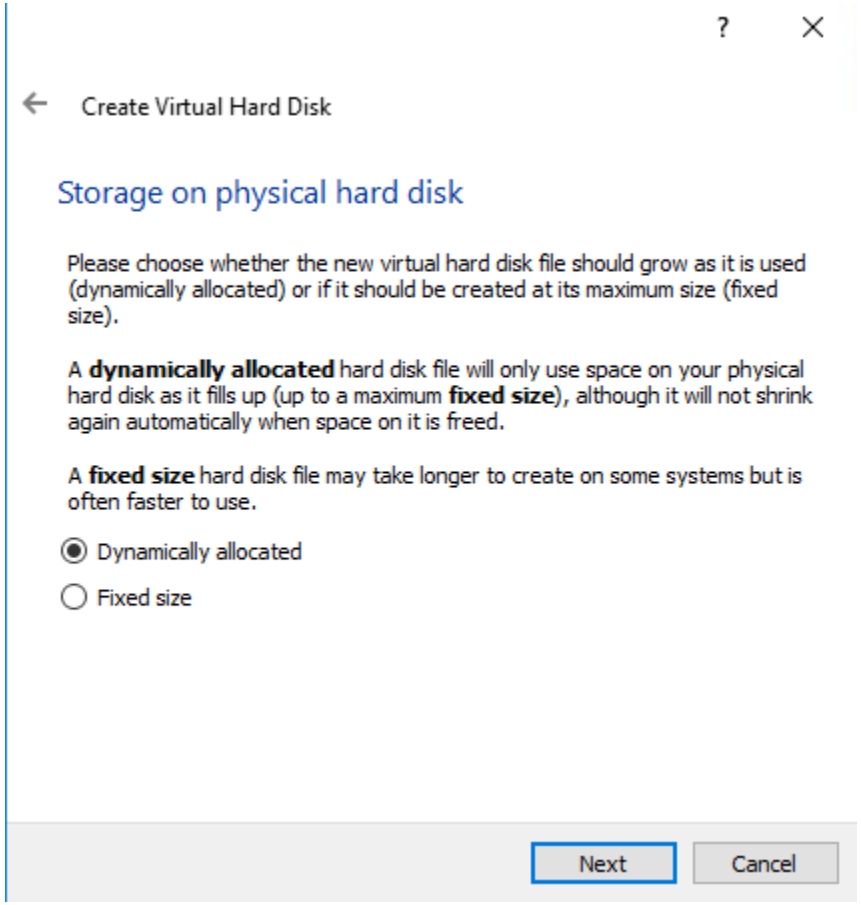


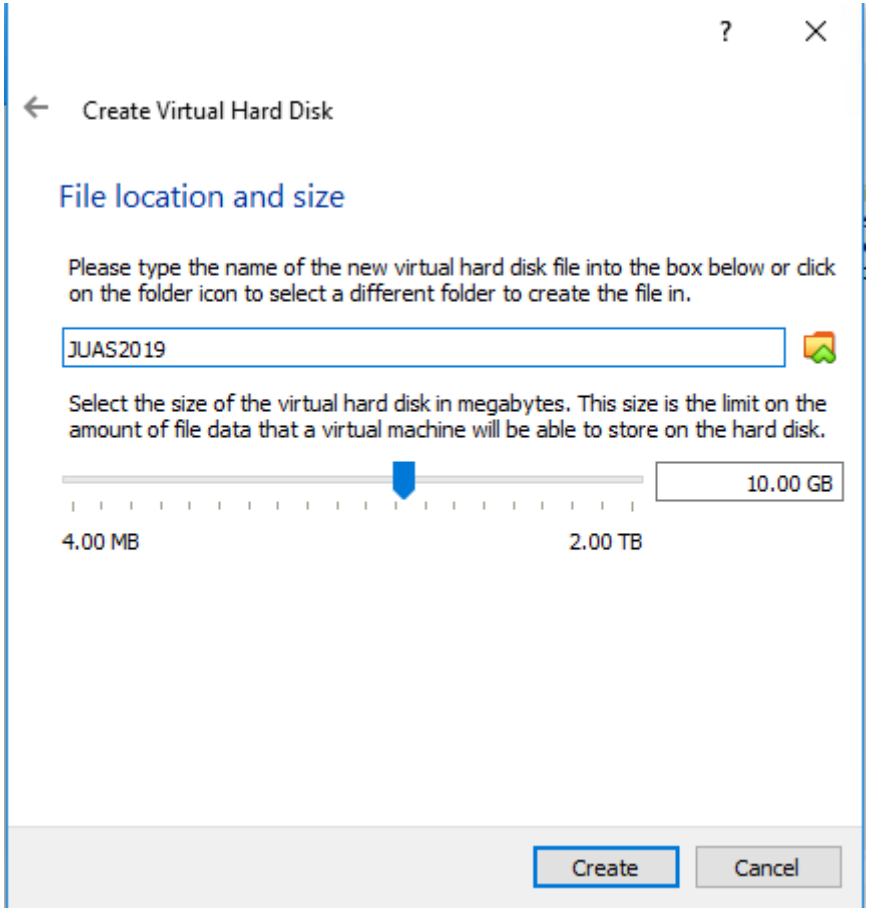


→ 2 GB is recommended by Ubuntu. This setting can be modified later.


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 10.00 GB.
Do not add a virtual hard disk
Create a virtual hard disk now
Use an existing virtual hard disk file
Empty
Create
Cancel

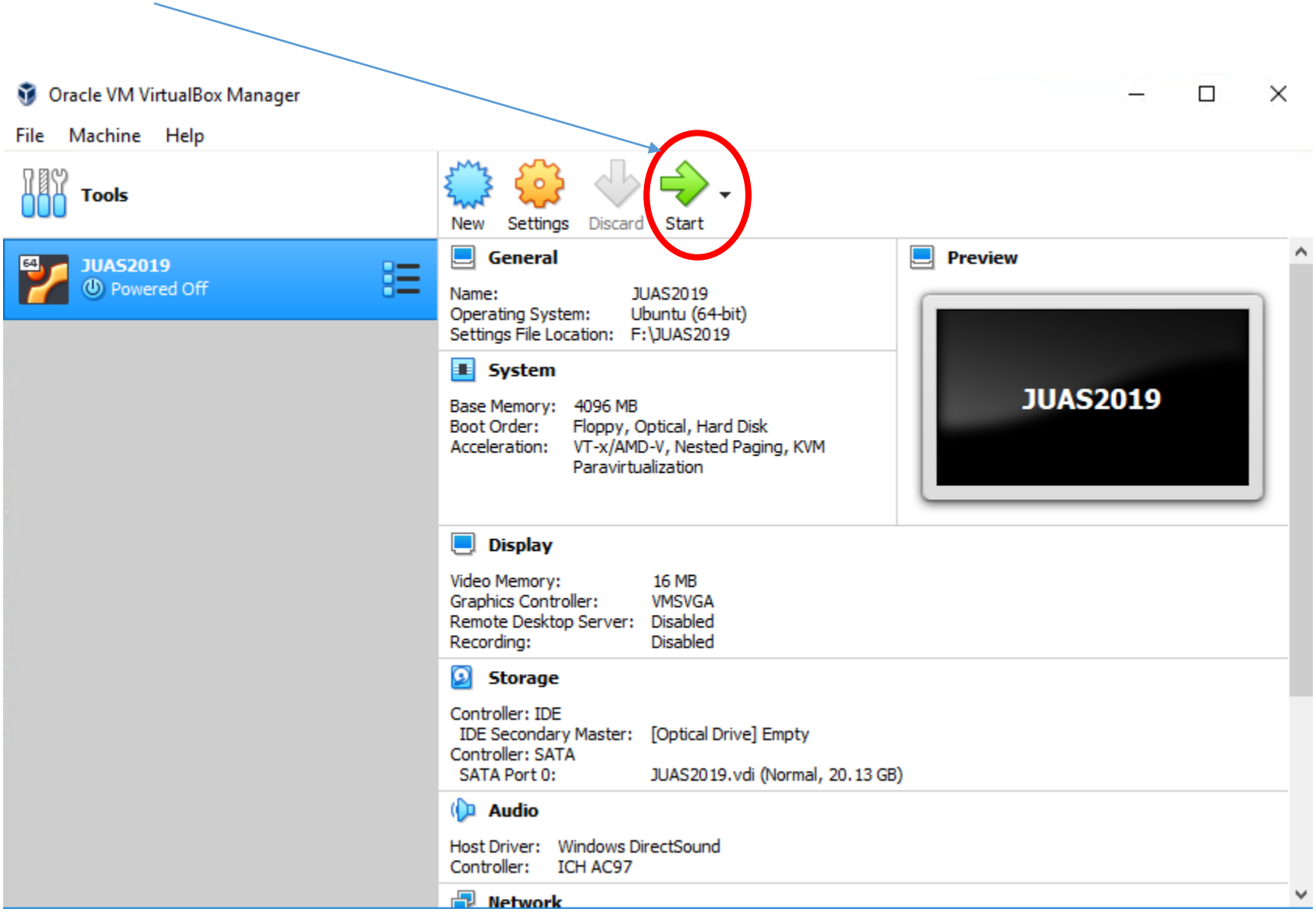

Create Virtual Hard Disk
Hard disk file type
Please choose the type of file that you would like to use for the new virtual hard disk. If you do not need to use it with other virtualization software you can leave this setting unchanged.
VDI (VirtualBox Disk Image)
VHD (Virtual Hard Disk)
VMDK (Virtual Machine Disk)
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
Tools
New
Settings
Discard
Start
JUAS2019
Powered Off
General
Name: JUAS2019
Operating System: Ubuntu (64-bit)
Settings File Location: F:\JUAS2019
System
Base Memory: 4096 MB
Boot Order: Floppy, Optical, Hard Disk
Acceleration: VT-x/AMD-V, Nested Paging, KVM Paravirtualization
Preview
JUAS2019
Display
Video Memory: 16 MB
Graphics Controller: VMSVGA
Remote Desktop Server: Disabled
Recording: Disabled
Storage
Controller: IDE
IDE Secondary Master: [Optical Drive] Empty
Controller: SATA
SATA Port 0: JUAS2019.vdi (Normal, 20.13 GB)
Audio
Host Driver: Windows DirectSound
Controller: ICH AC97
Network

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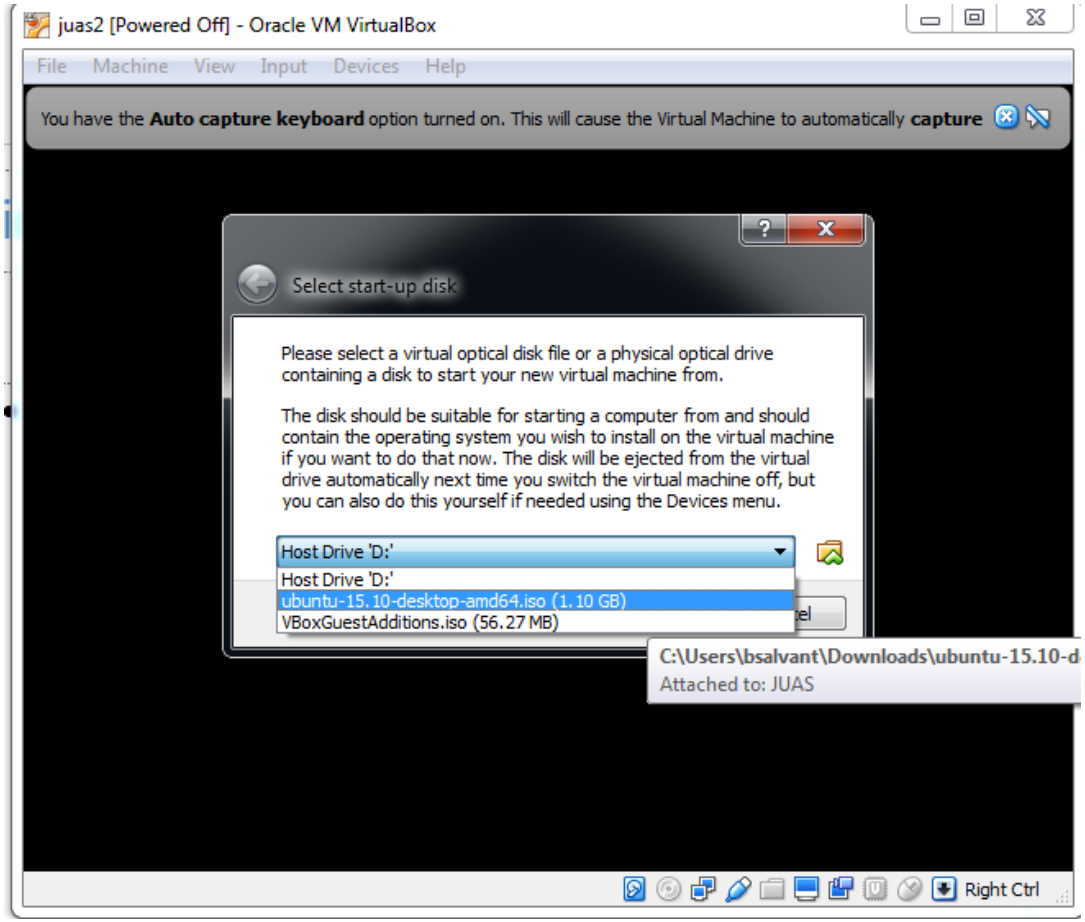
Download ubuntu

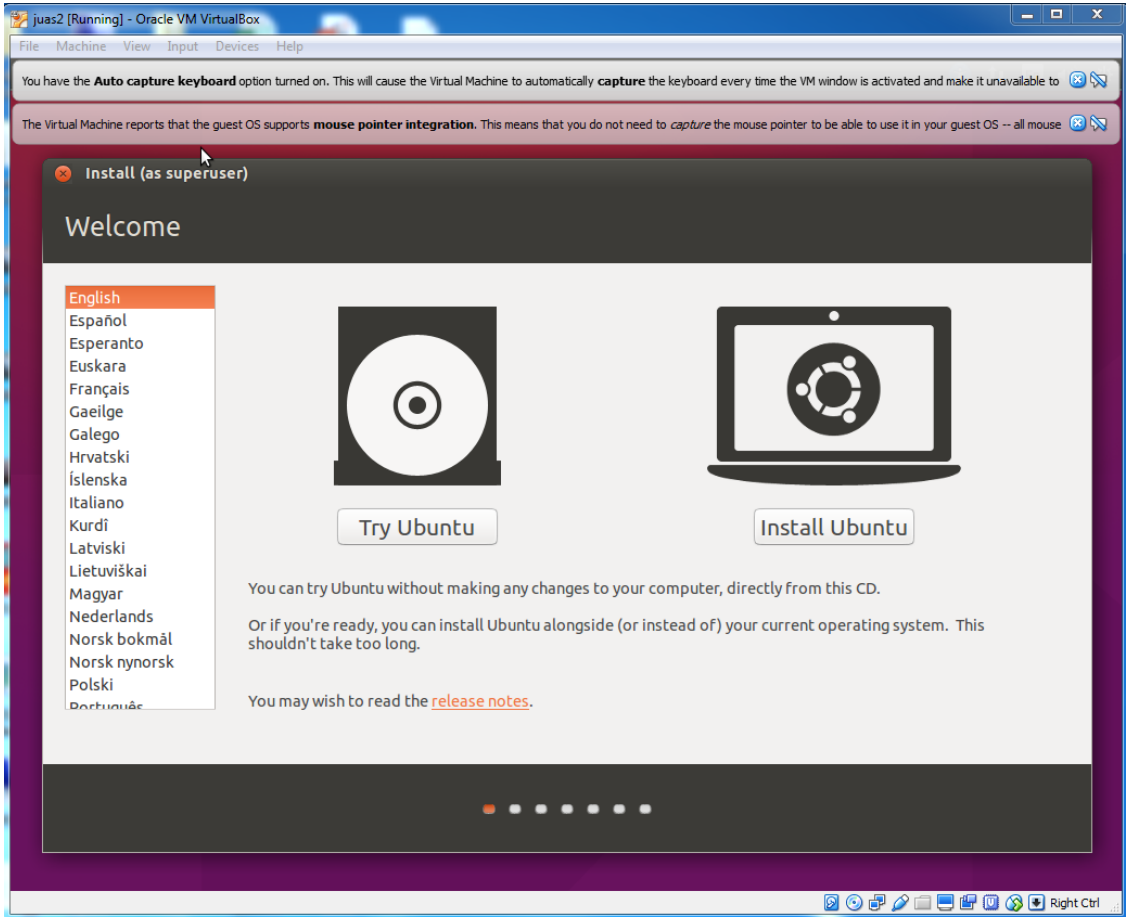
- https://www.ubuntu.com/download/desktop

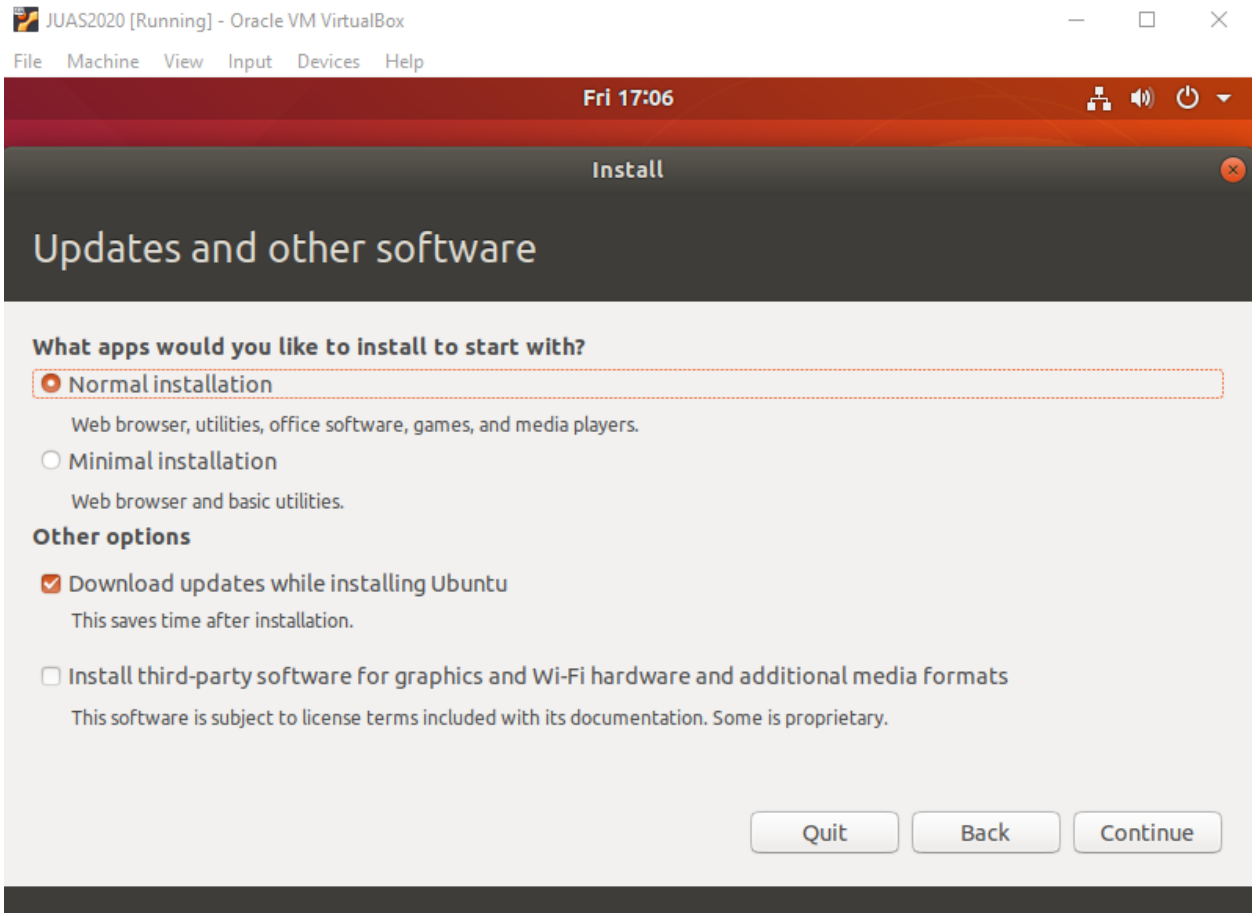
Select Ubuntu start up disk



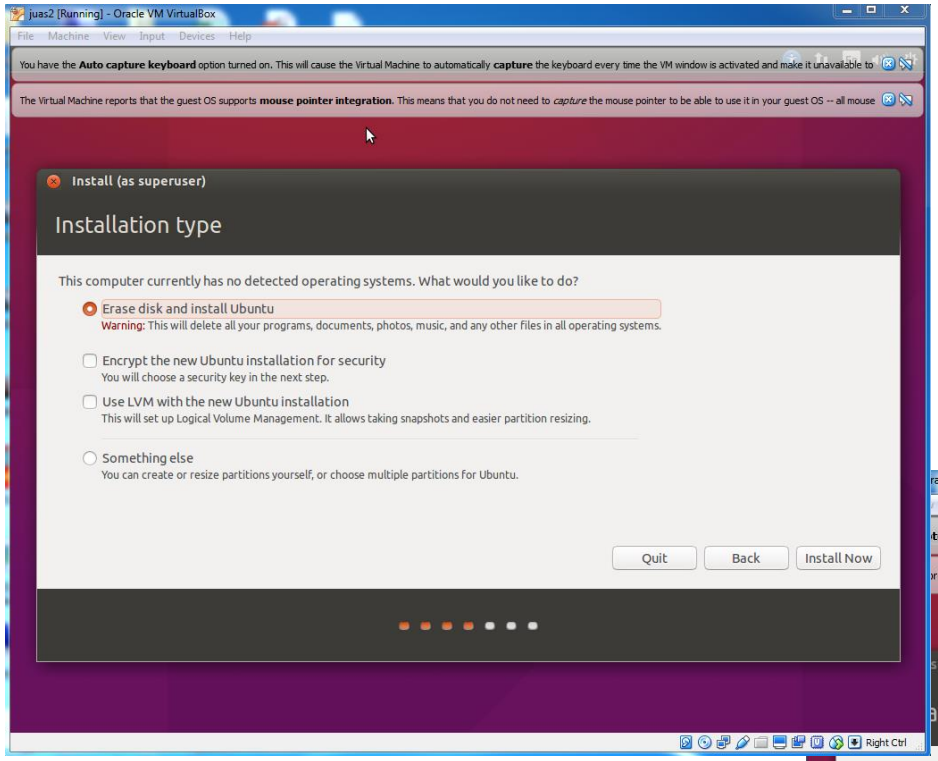
You may have to click on the small green arrow to browse for your Ubuntu installation image

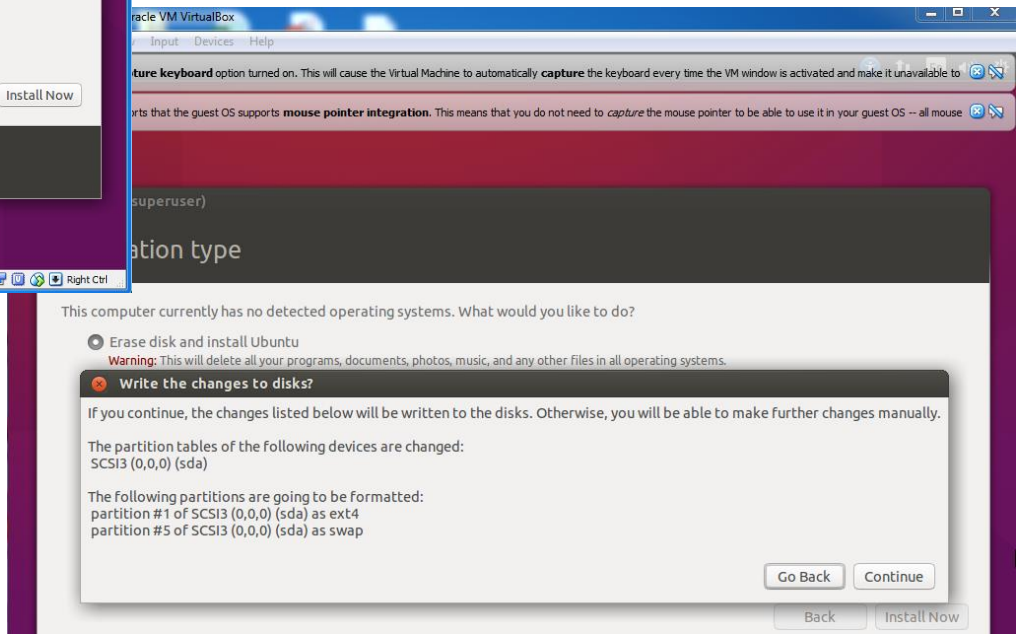
Install ubuntu




JUAS2020 [Running] - Oracle VM VirtualBox
File Machine View Input Devices Help
Fri 17:06
Install
Updates and other software
What apps would you like to install to start with?
Normal installation
Web browser, utilities, office software, games, and media players.
Minimal installation
Web browser and basic utilities.
Other options
Download updates while installing Ubuntu
This saves time after installation.
Install third-party software for graphics and Wi-Fi hardware and additional media formats
This software is subject to license terms included with its documentation. Some is proprietary.
Quit
Back
Continue

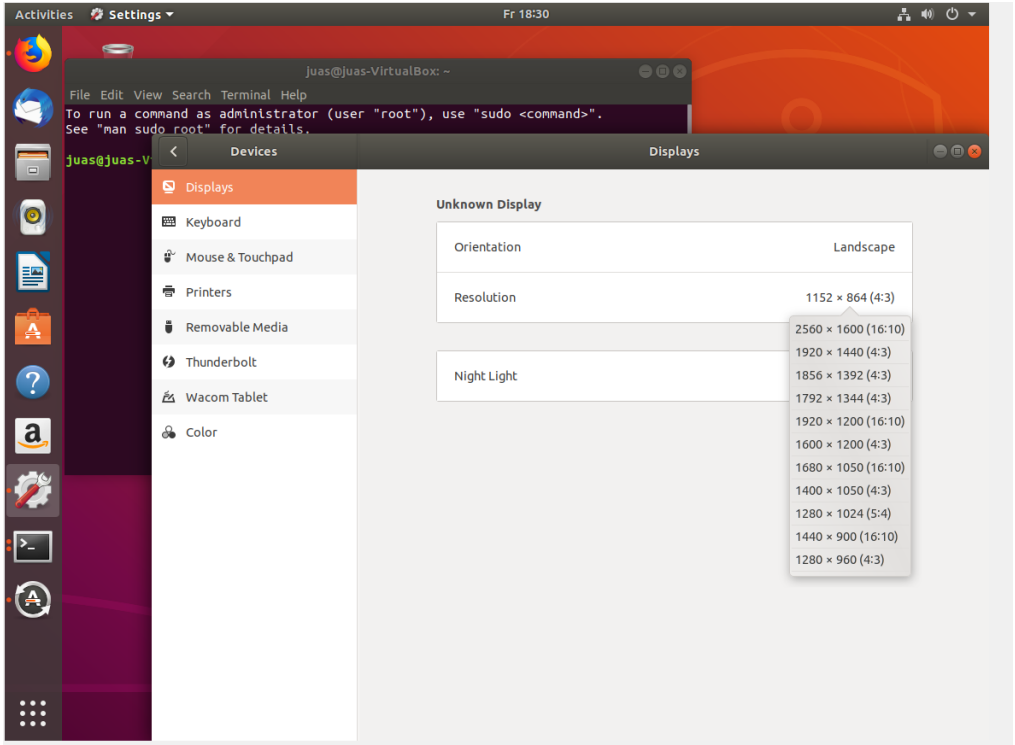
Keep default installation and “install now” and confirm with “continue” on the pop up





Then choose time zone and login details

- Then wait for file copy and Ubuntu installation restart the machine after it is complete
- If the screen is too small, change the display settings inside Ubuntu



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Install anaconda

Download anaconda for Linux at
https://www.anaconda.com/distribution/#download-section

or type

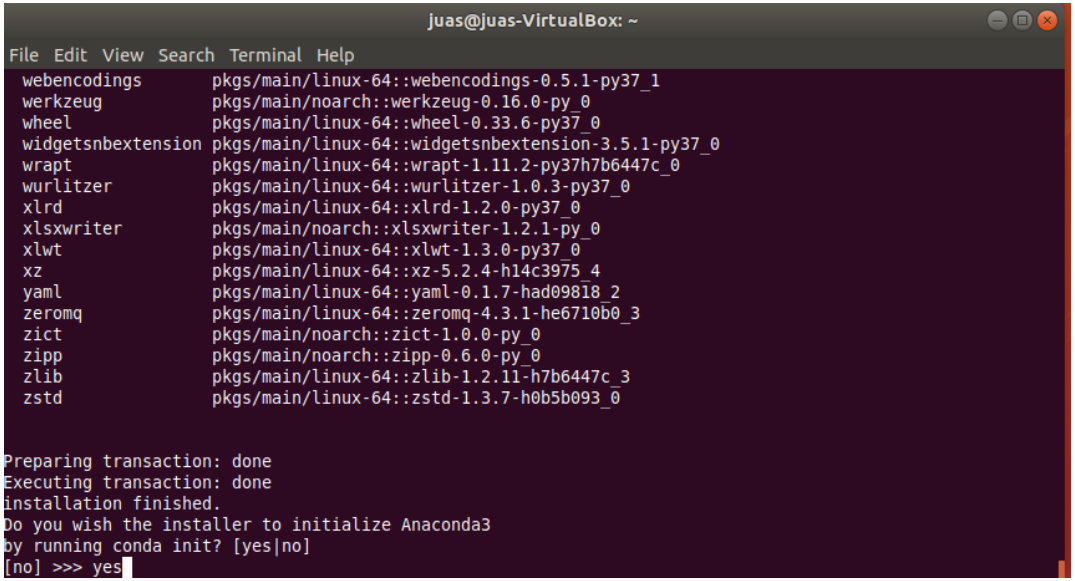
> wget https://repo.anaconda.com/archive/Anaconda3-2019.10-Linux-x86_64.sh

→ Then install it by typing

> sh Anaconda3-2019.0-Linux86_64.sh

In the download directory

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



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

→ Anaconda contains all the necessary libraries to run PyHEADTAIL.

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Installing PyHEADTAIL

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

```
(base) juas@juas-VirtualBox:~/PyHEADTAIL$ sudo apt-get install gcc
(base) juas@juas-VirtualBox:~/PyHEADTAIL$ pip install PyHEADTAIL
```

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

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

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

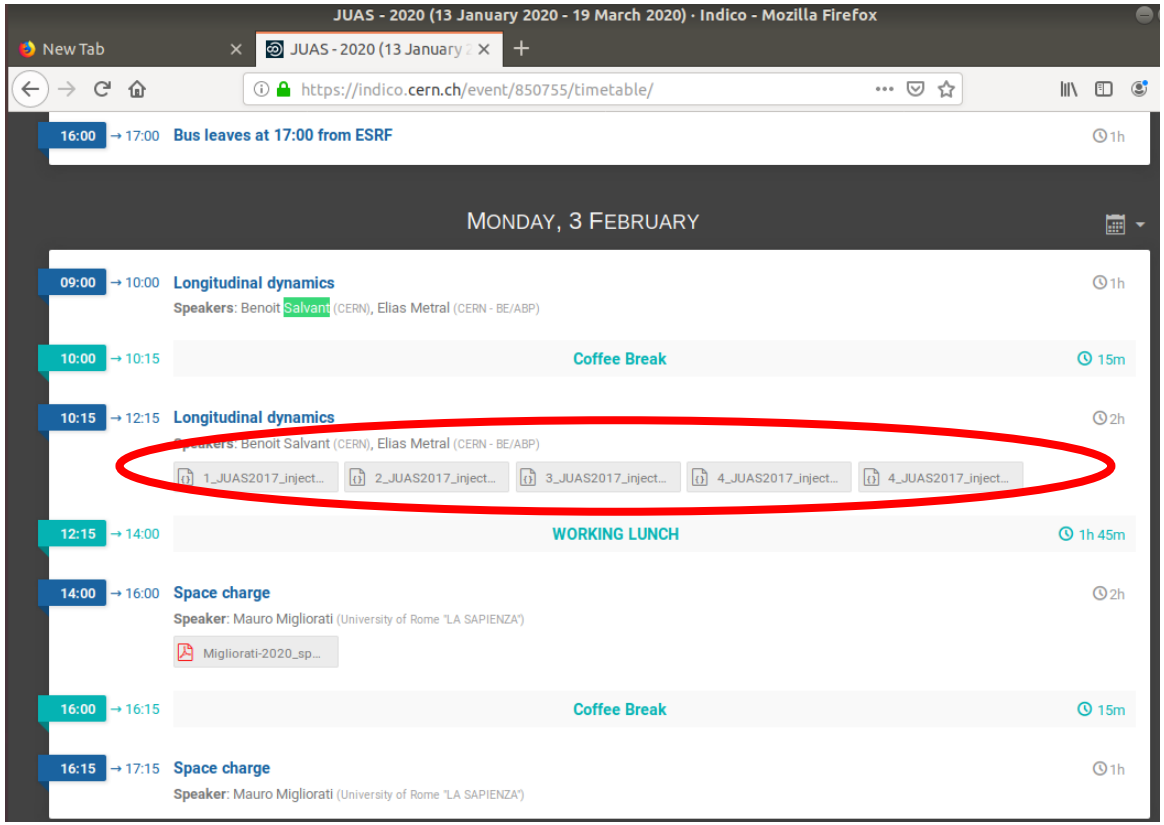
This only updates once a new terminal is opened (or do source ~/.bashrc)

In case of issues with PyHEADTAIL installation, most likely it is that fortran and C need to be installed:

- sudo apt-get install gfortran
- Sudo apt-get install gcc

Finding the examples

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



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

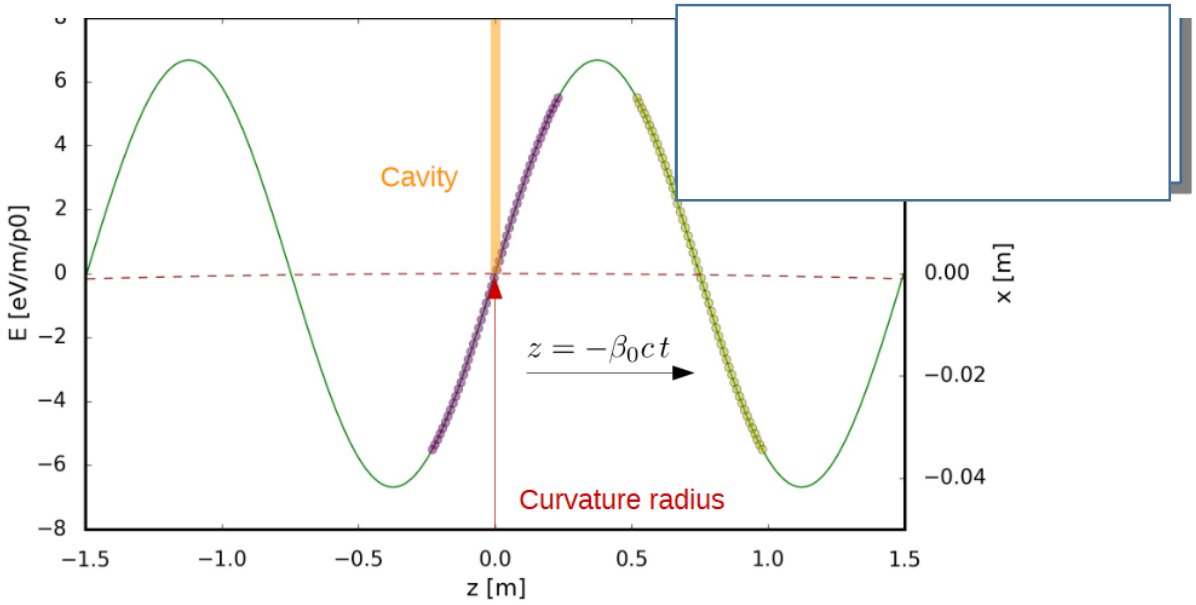
Changing variables

- 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 $$\Delta \mathrm{E}[GeV] = \frac{\Delta p}{p} 0.938\, \gamma \beta^2$$