

✓ BPL_IEC_operation script with FMPy

The key library FMPy is installed.

After the installation a small application BPL_IEC_operation is loaded and run. You can continue with this example if you like.

```
!lsb_release -a # Actual VM Ubuntu version used by Google
```

```

No LSB modules are available.
Distributor ID: Ubuntu
Description:    Ubuntu 22.04.4 LTS
Release:        22.04
Codename:       jammy

```

```
%env PYTHONPATH=
```

```
env: PYTHONPATH=
```

```
!python --version
```

```
Python 3.11.11
```

```

!wget https://repo.anaconda.com/miniconda/Miniconda3-py311_24.11.1-0-Linux-x86_64.sh
!chmod +x Miniconda3-py311_24.11.1-0-Linux-x86_64.sh
!bash ./Miniconda3-py311_24.11.1-0-Linux-x86_64.sh -b -f -p /usr/local
import sys
sys.path.append('/usr/local/lib/python3.11/site-packages/')

```

```

--2025-02-08 16:18:28-- https://repo.anaconda.com/miniconda/Miniconda3-py311_24.11.1-0-Linux-x86_64.sh
Resolving repo.anaconda.com (repo.anaconda.com)... 104.16.32.241, 104.16.191.158, 2606:4700::6810:bf9e, ..
Connecting to repo.anaconda.com (repo.anaconda.com)|104.16.32.241|:443... connected.
HTTP request sent, awaiting response... 200 OK
Length: 145900576 (139M) [application/octet-stream]
Saving to: 'Miniconda3-py311_24.11.1-0-Linux-x86_64.sh'

```

```
Miniconda3-py311_24 100%[=====] 139.14M 158MB/s in 0.9s
```

```
2025-02-08 16:18:29 (158 MB/s) - 'Miniconda3-py311_24.11.1-0-Linux-x86_64.sh' saved [145900576/145900576]
```

```

PREFIX=/usr/local
Unpacking payload ...

```

```
Installing base environment...
```

```

Preparing transaction: ...working... done
Executing transaction: ...working... done
installation finished.

```

```
!conda update -n base -c defaults conda --yes
```

```

Channels:
- defaults
Platform: linux-64
Collecting package metadata (repodata.json): done
Solving environment: done

```

```
## Package Plan ##
```

```
environment location: /usr/local
```

```

added / updated specs:
- conda

```

The following packages will be downloaded:

package	build	
ca-certificates-2024.12.31	h06a4308_0	128 KB
certifi-2025.1.31	py311h06a4308_0	163 KB

Total: 291 KB

The following packages will be UPDATED:

ca-certificates	2024.11.26-h06a4308_0 --> 2024.12.31-h06a4308_0
certifi	2024.8.30-py311h06a4308_0 --> 2025.1.31-py311h06a4308_0

Downloading and Extracting Packages:

certifi-2025.1.31	163 KB	: 0% 0/1 [00:00<?, ?it/s]
ca-certificates-2024	128 KB	: 0% 0/1 [00:00<?, ?it/s]
certifi-2025.1.31	163 KB	: 100% 1.0/1 [00:00<00:00, 10.85it/s]
ca-certificates-2024	128 KB	: 100% 1.0/1 [00:00<00:00, 9.28it/s]

Preparing transaction: done
Verifying transaction: done
Executing transaction: done

```
!conda --version
!python --version
```

```
🔄 conda 24.11.1
   Python 3.11.11
```

```
!conda config --set channel_priority strict
```

```
!conda install -c conda-forge fmpy --yes # Install the key package
```

```
🔄
```

```
#!conda install matplotlib --yes
```

Now specific installation and the run simulations. Start with connecting to Github. Then upload the two files:

- FMU - BPL_IEC_operation_linux_om_me.fmu
- Setup-file - BPL_IEC_operation_fmpy_explore.py

```
%bash
git clone https://github.com/janpeter19/BPL_IEC_operation
```

📂 Cloning into 'BPL_IEC_operation'...

```
%cd BPL_IEC_operation
```

📂 /content/BPL_IEC_operation

✓ BPL_IEC_operation

Authors: Karl Johan Brink and Jan Peter Axelsson

In this notebook we show operation of a typical ion-exchange chromatography step. The impact of pH is also illustrated.

The model is based on the simplified model [1].

```
run -i BPL_IEC_fmpy_explore.py
```

📂 Linux - run FMU pre-compiled OpenModelica

Model for bioreactor has been setup. Key commands:

- par() - change of parameters and initial values
- init() - change initial values only
- simu() - simulate and plot
- newplot() - make a new plot
- show() - show plot from previous simulation
- disp() - display parameters and initial values from the last simulation
- describe() - describe culture, broth, parameters, variables with values/units

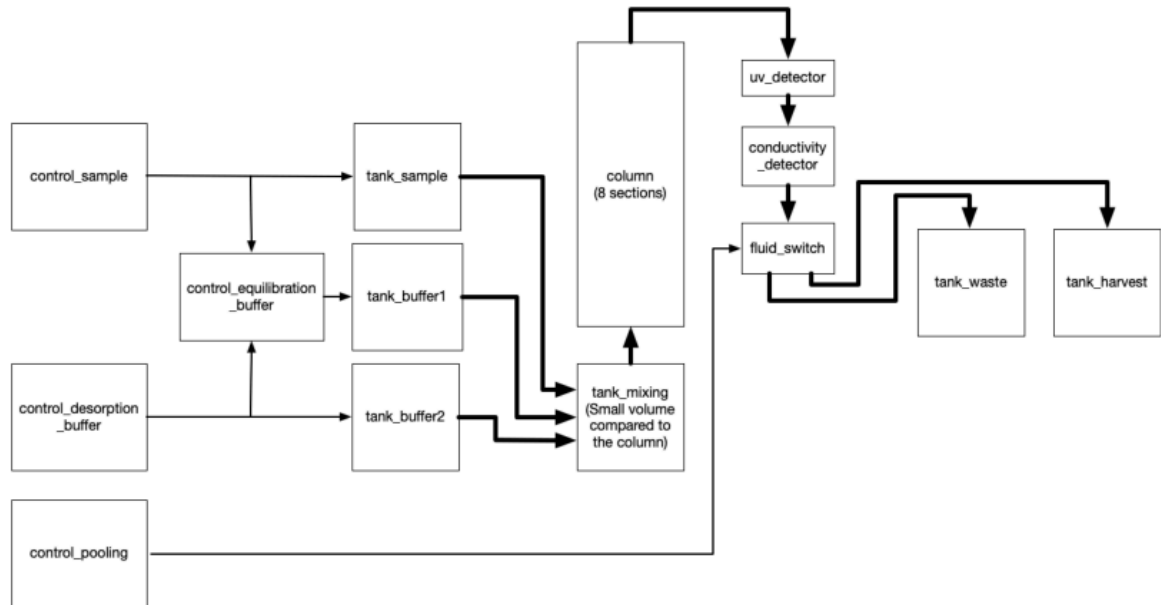
Note that both disp() and describe() takes values from the last simulation and the command process_diagram() brings up the main configuration

Brief information about a command by help(), eg help(simu)
Key system information is listed with the command system_info()

```
plt.rcParams['figure.figsize'] = [30/2.54, 24/2.54]
```

```
# The process diagram is made outside Modelica to illustrate the configuration
process_diagram()
```

➡ No processDiagram.png file in the FMU, but try the file on disk.



✓ 1 Typical parameters an ion exchange chromatography column step

From given column height (h) diameter (d) and linear flow rate (lfr)
 # actual column volume (V) and volume flow rate (VFR) are calculated below.

```

from numpy import pi
h = 20.0
d = 1.261
a = pi*(d/2)**2
V = h*a
print('V =', np.round(V,1), '[mL]')

lfr = 48
VFR = a*lfr/60
print('VFR =', np.round(VFR,1), '[mL/min]')
```

➡ V = 25.0 [mL]
 VFR = 1.0 [mL/min]

Sample concentration product P_in and antagonist A_in

```

par(P_in = 1.0)
par(A_in = 1.0)
par(E_in = 0.0)
```

Column properties are described by the size and binding capacity of the resin Q_av

```

par(height = h)
par(diameter = d)
par(Q_av = 6.0)
```

Resin parameters – default values used

Remaining salt concentration in the column from previous batch and eliminated during the initial equilibration
 init(E_start = 50)

Salt concentration of the desorption buffer

```

par(E_in_desorption_buffer = 8.0)
```

Flow rate rate through the

```

par(LFR=lfr)
```

Switching points during operation are conveniently described in terms of multiples of the column volume V

```

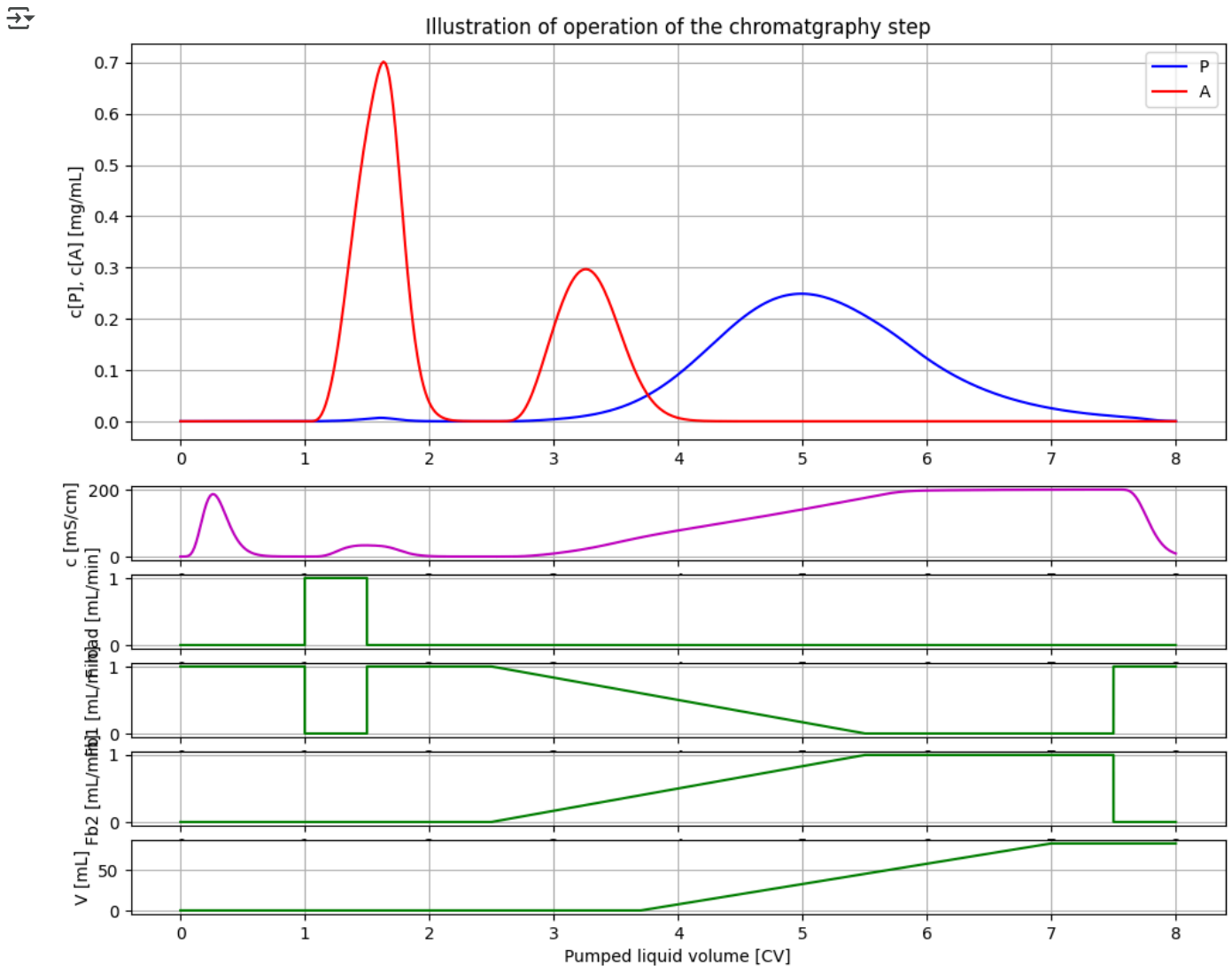
CV_ekv = 1.0
CV_ads = 0.5
```

```

CV_wash = 1.0
CV_desorb = 3.0
CV_start_pool = 1.2
CV_stop_pool = 4.5
CV_wash2 = 2.5
par(scale_volume=True, start_adsorption=CV_ekv*V, stop_adsorption=(CV_ekv+CV_ads)*V)
par(start_desorption=(CV_ekv+CV_ads+CV_wash)*V, stationary_desorption=(CV_ekv+CV_ads+CV_wash+CV_desorb)*V)
par(stop_desorption=7.5*V)
par(start_pooling=(CV_ekv+CV_ads+CV_wash+CV_start_pool)*V, stop_pooling=(CV_ekv+CV_ads+CV_wash+CV_stop_pool)*V)

# Simulation and plot of results
newplot(title='Illustration of operation of the chromatography step', plotType='Elution-conductivity-vs-CV-com
simu((CV_ekv+CV_ads+CV_wash+CV_desorb+CV_wash2)*V/VFR)

```



Comments of steps of operations: 1) Time: 0-1 hours - equilibration. Just to illustrate the equilibration process the first part of the column is given an initial value of salt concentration. 2) Time: 1-1.5 hours - sample is loaded on the column. The product P is adsorbed to the column and just a small amount passes through and goes to the waste. The antagonist A is much less adsorbed. 3) Time: 1.5-2.5 hours - washing 1. The column comes to equilibrium and both antagonist and product comes down to low levels. 4) Time: 2.5-5.5 hours - desorption. A linear gradient of increasing salt concentration is applied. First the antagonist and later the product comes out. 5) Time: 5.5-7.5 hours - washing 2. The column has constant salt concentration and stationary desorption. 6) Time: 3.7-7.0 hours - pooling of product. The start- and stop of pooling are chosen with trade-off between maximizing the product pooled and minimize the amount of antagonist in the pooling. 7) Time: 7.5-8.0 hours - desorption stopped and salt is washed out and preparation of the next batch to come.

Note that step 4 and 5 is parallel to step 6.

```
# Check mass-balance of P and A
P_mass = model_get('tank_harvest.m[1]') + model_get('tank_waste.m[1]')
A_mass = model_get('tank_harvest.m[2]') + model_get('tank_waste.m[2]')
print('P_mass [mg] =', P_mass)
print('A_mass [mg] =', A_mass)
```

```
➦ P_mass [mg] = 12.422130344957237
  A_mass [mg] = 12.488781164503445
```

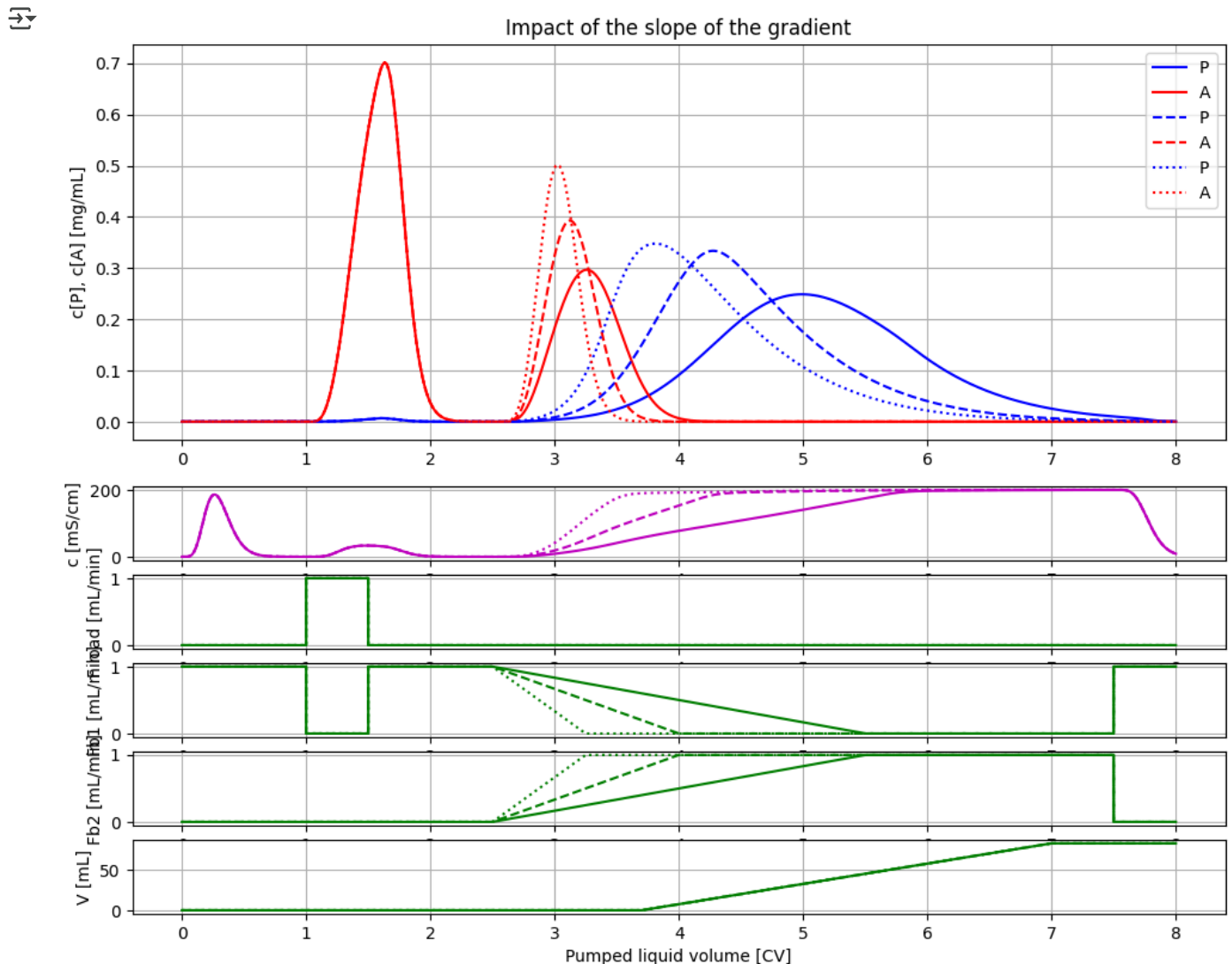
✓ 2 The impact of the slope of the desorption gradient

```
# Simulations showing the impact of change of slope of the desorption gradient
newplot(title='Impact of the slope of the gradient', plotType='Elution-conductivity-vs-CV-combined-all')

# Same gradient as before
par(start_desorption=(CV_ekv+CV_ads+CV_wash)*V, stationary_desorption=(CV_ekv+ CV_ads+CV_wash+CV_desorb)*V)
par(stop_desorption=7.5*V)
simu((CV_ekv+CV_ads+CV_wash+CV_desorb+CV_wash2)*V/VFR)

# Gradient finishes after 0.5 of the volume
par(stationary_desorption = (CV_ekv + CV_ads + CV_wash + 0.5*CV_desorb)*V )
simu((CV_ekv+CV_ads+CV_wash+CV_desorb+CV_wash2)*V/VFR)

# Gradient finishes after 0.25 of the volume
par(stationary_desorption = (CV_ekv + CV_ads + CV_wash + 0.25*CV_desorb)*V )
simu((CV_ekv+CV_ads+CV_wash+CV_desorb+CV_wash2)*V/VFR)
```



✓ 3 The impact of salt concentration in the sample

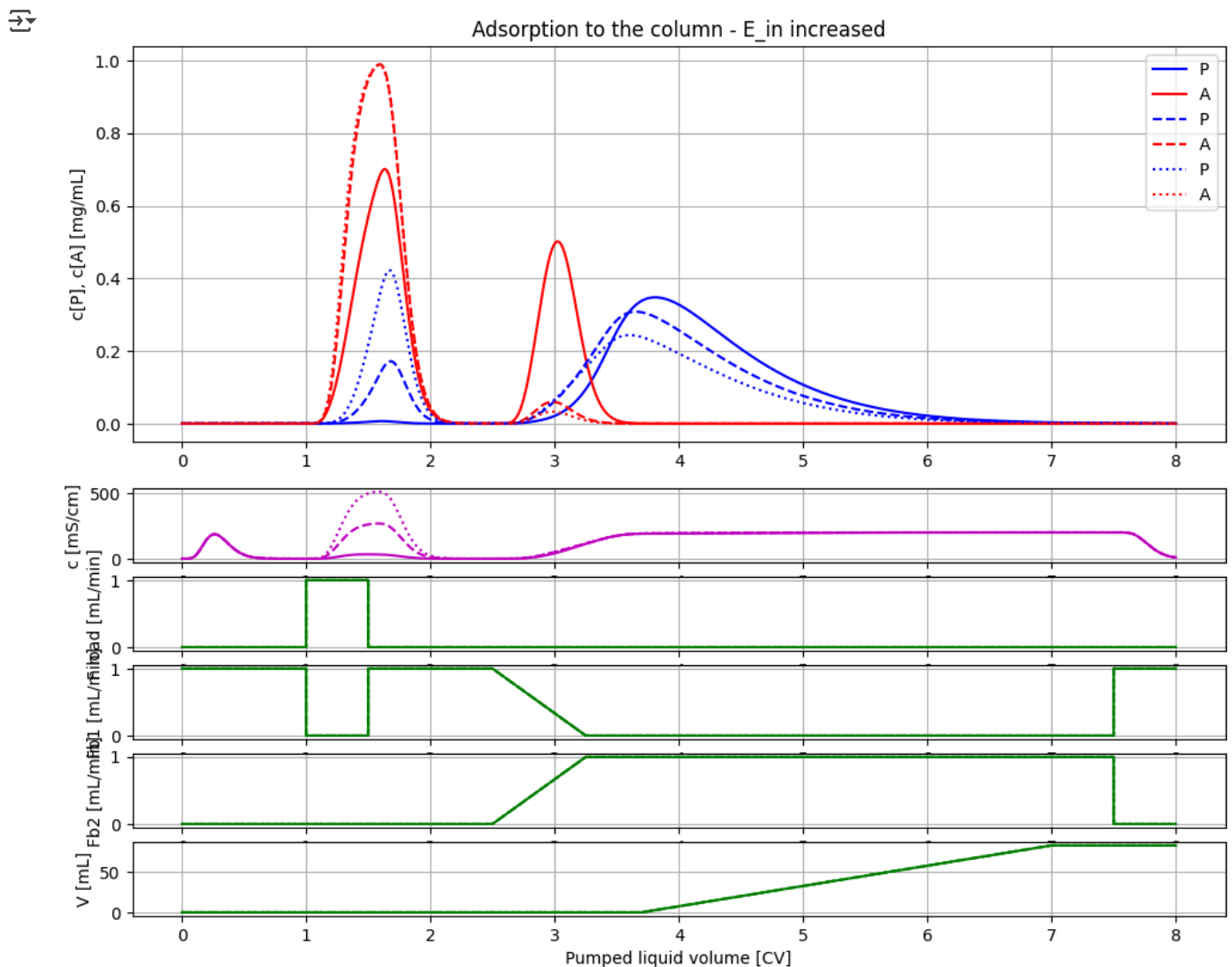
These values should be compared with the expected value 12.5 mg, i.e. half a column volume with sample concentration 1 mg/L. The difference is due to numerical errors during simulation.

```
# Let us investigate the impact of increasing salt concentration in the sample E_in

# Simulate and plot the results
newplot(title='Adsorption to the column - E_in increased', plotType='Elution-conductivity-vs-CV-combined-all'

for value in [0, 10, 20]:
    par(E_in=value)
    simu((CV_ekv+CV_ads+CV_wash+CV_desorb+CV_wash2)*V/VFR)

# Restore default values
par(k2=0.05, k4=0.3, E_in=0)
```



Note, that increased salt concentration in the sample affect binding of both proteins. During adsorption less is bound. During desorption less product P can be harvested but the fraction of antagonist A may be lowered. Thus, some product is lost but the quality in terms of purity is improved.

✓ 4 The impact of change of binding strength due to pH

There are many factors that contribute to the binding strength. A most important factor is the pH-value of the resin and the characteristic iso-electric point of the protein. The binding strenght can be seen as proportional to the difference.

The binding strength of the resin is described by the quotient $KP=k_1/k_2$ for the protein P and similarly $KA=k_3/k_4$ for the protein A.

Below a few help-functions that describe this idea of the pH difference and its impact on binding strength in terms of the parameters k_1 , k_2 , k_3 , and k_4 of the protein-resin interaction.

```
# Define function that describe the proportionality of binding strength ot
# the pH difference of the iso-electric point and the resin

def KP_pH_sensitivity(pI_P=8.0, pH_resin=7.0):
    K_P_nom = 0.0
    coeff_pH = 6.0
    return K_P_nom + coeff_pH*(pI_P-pH_resin)

def KA_pH_sensitivity(pI_A=7.1667, pH_resin=7.0):
    K_A_nom = 0.0
    coeff_pH = 1.0
    return K_A_nom + coeff_pH*(pI_A-pH_resin)

def par_pH(pI_P=8.0, pI_A=7.1667, pH_resin=7.0, TP=3.33, TA=20.0):
    if (pI_P > pH_resin) & (pI_A > pH_resin):
        par(k2 = 1/(TP*KP_pH_sensitivity(pI_P=pI_P, pH_resin=pH_resin)))
        par(k4 = 1/(TA*KA_pH_sensitivity(pI_A=pI_A, pH_resin=pH_resin)))
    else:
        print('Both pI_P > pH_resin and pI_A > pH_resin must hold - no parameter change made')

# The default parameters of the column
disp('column')

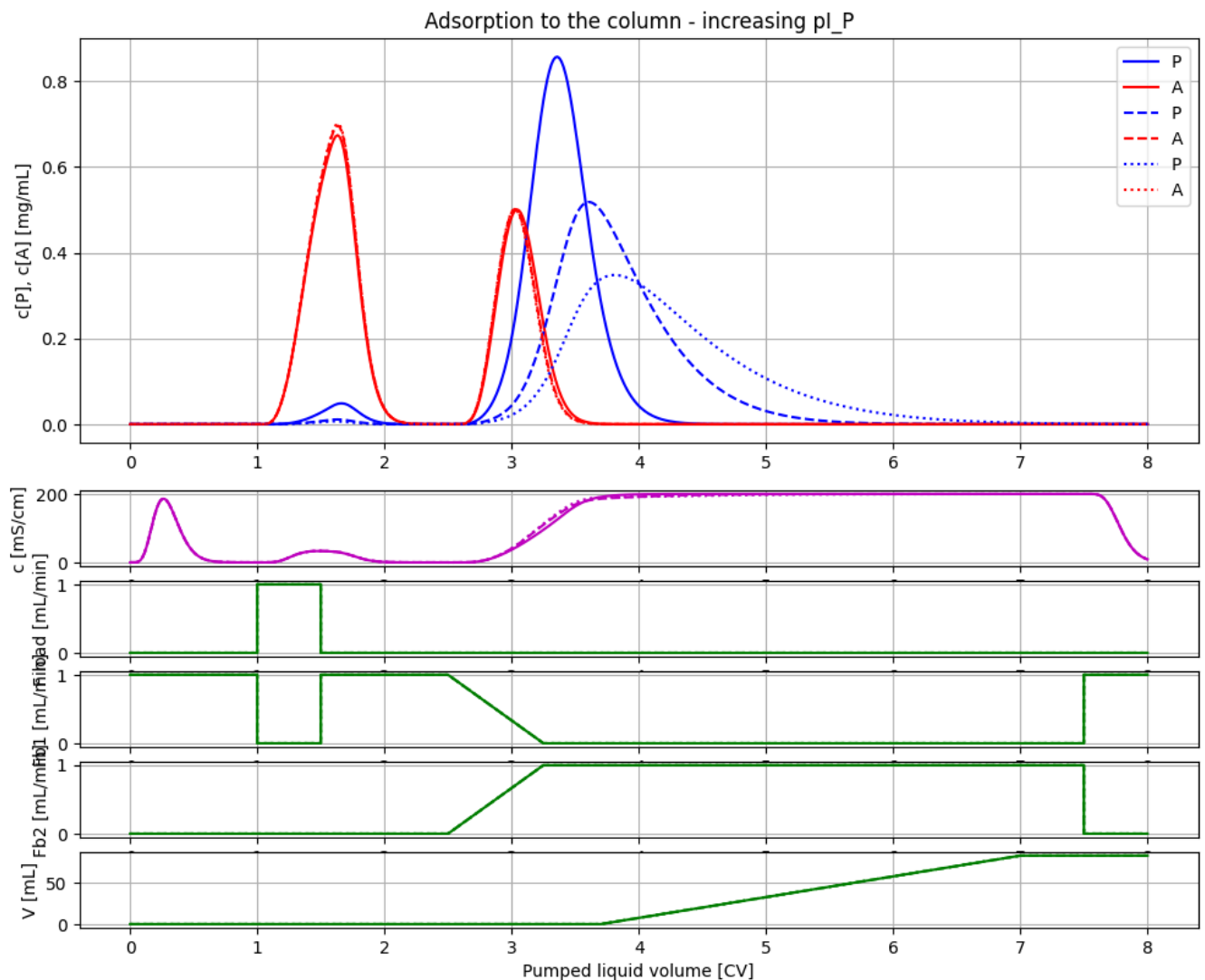
↩ diameter : 7.136
height : 20.0
x_m : 0.3
k1 : 0.3
k2 : 0.05
k3 : 0.05
k4 : 0.3
Q_av : 3.0
E_start : 0.0

# Let us investigate the impact of change of the iso-electric pH for protein P

# Simulate and plot the results
newplot(title='Adsorption to the column - increasing pI_P', plotType='Elution-conductivity-vs-CV-combined-all

for value in [7.2, 7.6, 8.0]:
    par_pH(pI_P=value, pI_A=7.1667, pH_resin=7.0)
    simu((CV_ekv+CV_ads+CV_wash+CV_desorb+CV_wash2)*V/VFR)

# Restore default values
par(k2 = 0.05, k4 = 0.3)
```

Note, with increasing pI_P the binding of P increase which leads less loss of product during adsorption. During desorption the peak height is lower with increasing binding strenght, but the total amoiunt of product P that can be harvested is higher, due to the smaller loss during adsorption.

```
# Let us investigate the impact of pI_P close to pH_resin
```

```
# Simulate and plot the results
```

```
newplot(title='Adsorption to the column - pI_P close to pH_resin', plotType='Elution-conductivity-vs-CV-combi
```

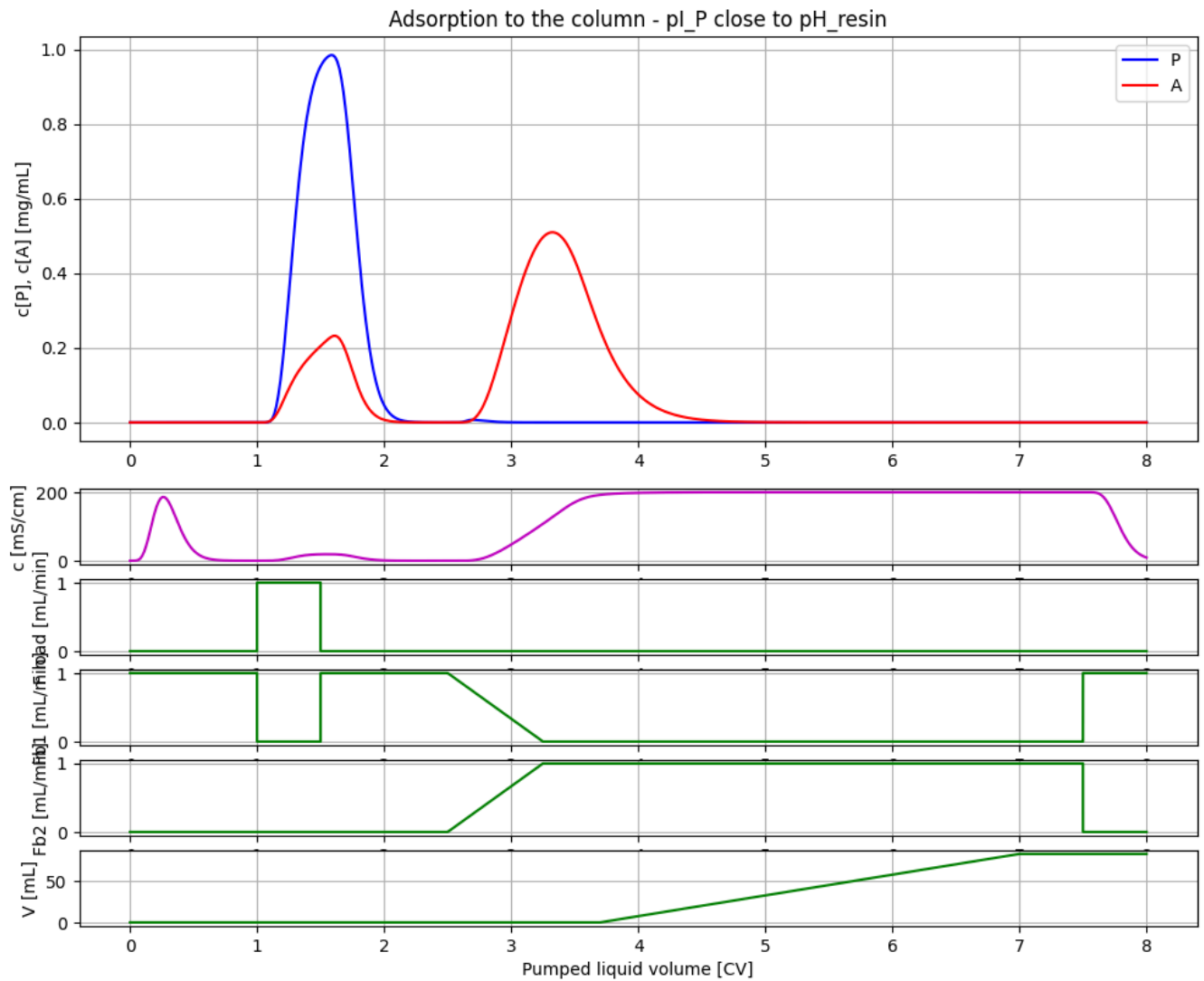
```
for value in [7.0001]:
```

```
    par_pH(pI_P=value, pI_A=8)
```

```
    simu((CV_ekv+CV_ads+CV_wash+CV_desorb+CV_wash2)*V/VFR)
```

```
# Restore default values
```

```
par(k2=0.05, k4=0.3)
```



```
# Let us investigate the impact of pI_A close to pH_resin
```

```
# Simulate and plot the results
```

```
newplot(title='Adsorption to the column - pI_A close to pH_resin', plotType='Elution-conductivity-vs-CV-combi
```

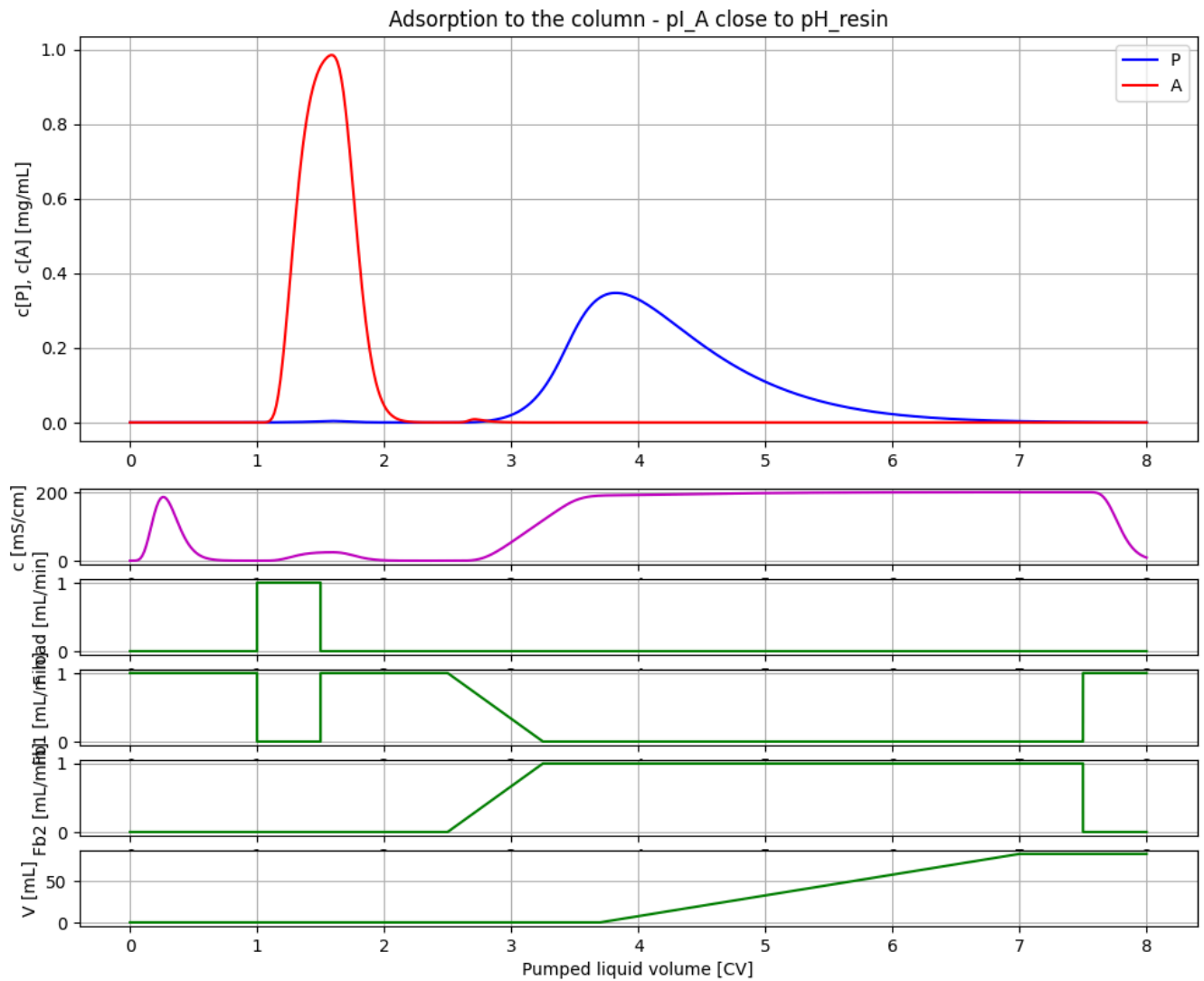
```
for value in [7.001]:
```

```
    par_pH(pI_P=8.0, pI_A=value)
```

```
    simu((CV_ekv+CV_ads+CV_wash+CV_desorb+CV_wash2)*V/VFR)
```

```
# Restore default values
```

```
par(k2=0.05, k4=0.3)
```



Let us also investigate the impact of salt concentration of the desorptions buffer

Simulate and plot the results

```
newplot(title='Adsorption to the column - desorption buffer salt conc varied', plotType='Elution-conductivity'
```

```
for value in [8.0, 16.0]:
```

```
    par(E_in_desorption_buffer=value)
```

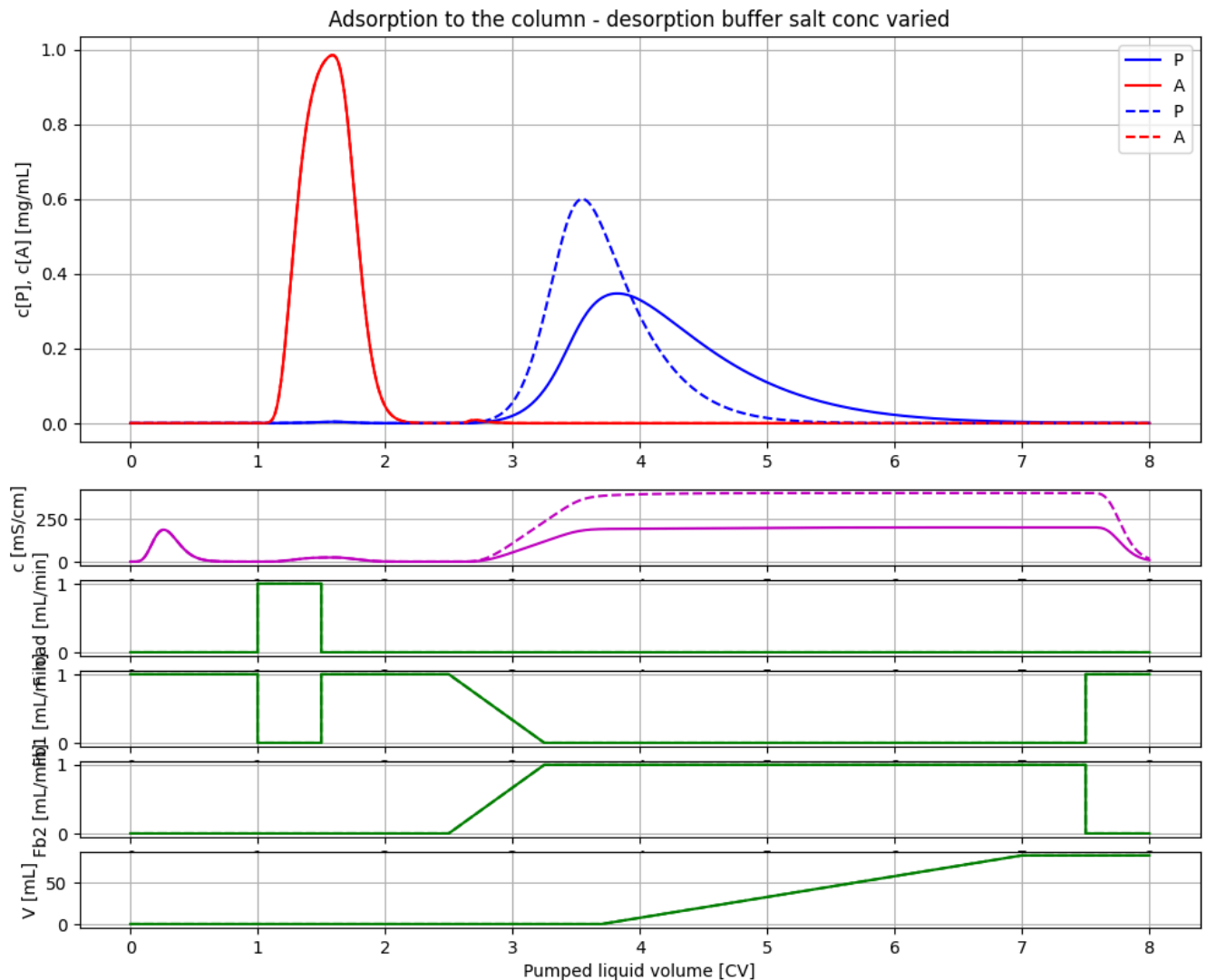
```
    par_pH(pI_P=8.0, pI_A=7.001, pH_resin=7.0)
```

```
    simu((CV_ekv+CV_ads+CV_wash+CV_desorb+CV_wash2)*V/VFR)
```

Restore default values

```
par(E_in_desorption_buffer=8.0)
```

```
par(k2=0.05, k4=0.3)
```



✓ 5 Breakthrough curve often used during process development

```
# Experiment to check column capacity Q_av often called breakthrough curve
par(P_in=1, A_in=0, E_in=0)
init(E_start = 0)
par(Q_av=6.0)

par(scale_volume=True, start_adsorption=1*V, stop_adsorption=4.01*V)
par(start_desorption=10*V, stationary_desorption=10.5*V, stop_desorption=11*V)
par(start_pooling=11*V, stop_pooling=12*V)

newplot(title='Impact of variation in column capacity Q_av', plotType='Elution-conductivity-vs-CV-combined-al
for value in [1, 2, 3, 6]: par(Q_av=value); simu(4.0*V/VFR)

# Linje för 10% UV
ax1.plot([0,4], [0.1,0.1], 'k--')

# Restore default parameters
par(Q_av=6.0, A_in=1.0)
```

