Tokamak GOLEM
Data processing

P. Macha, V. Svoboda

OUTLINE

- Motivation
- Data format and access
- WGET
- EXCEL
- GNUPLOT
- MATLAB
- OCTAVE
- PYTHON

Why do we need data processing?

- Data processing is the most important part of every experiment.
- Discharge produces various raw data.
- The data needs to be processed.
- Several processing tools can be used:
  - Programming languages - **Python**, MATLAB, GNUPLOT, Octave, etc.
  - Spreadsheets - Excel (not recommended).
- Main output - figures, tables, etc.

What is data processing?

1. Data collection - gather data from a source.
2. Sorting data - sort the raw data (remove incorrect data, remove offset, ...)
3. Data input - prepare the data for processing
4. Data processing - processing the data input (integrate, differentiate, sum, ...)
5. Data output - creating visualisation, figures, ...
6. Data storage - save the data (for the next use)

DATA ACCESS

- All the discharge outputs are available the GOLEM website

  http://golem.fjfi.cvut.cz/shots/<#shot_no>/

- The most recent discharge

  http://golem.fjfi.cvut.cz/shots/0

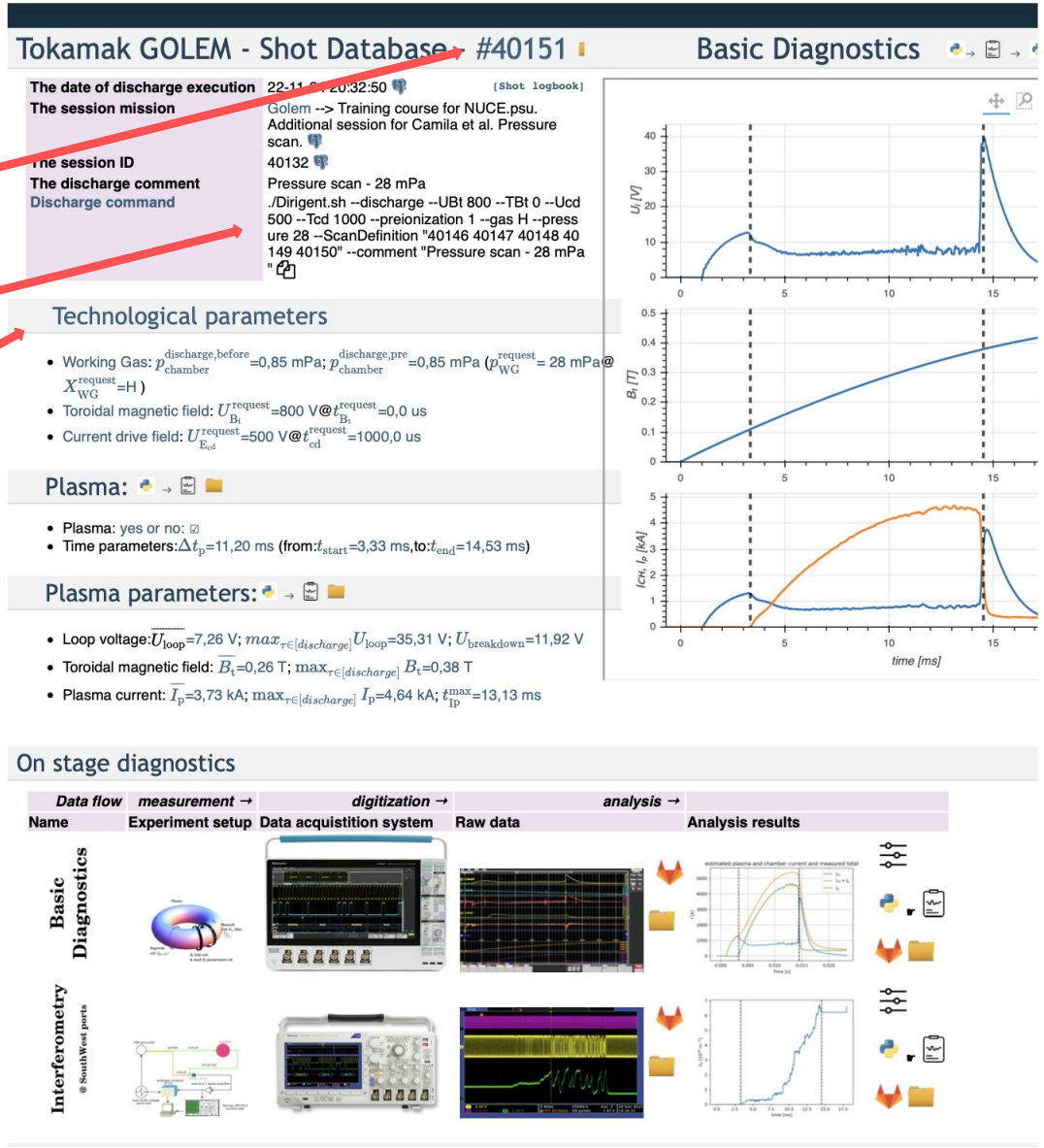
- Data <CHANNEL> from DAS <DAS_name>

  http://golem.fjfi.cvut.cz/shots/<#shot_no>/<DAS_name>/<CHANNEL>.csv

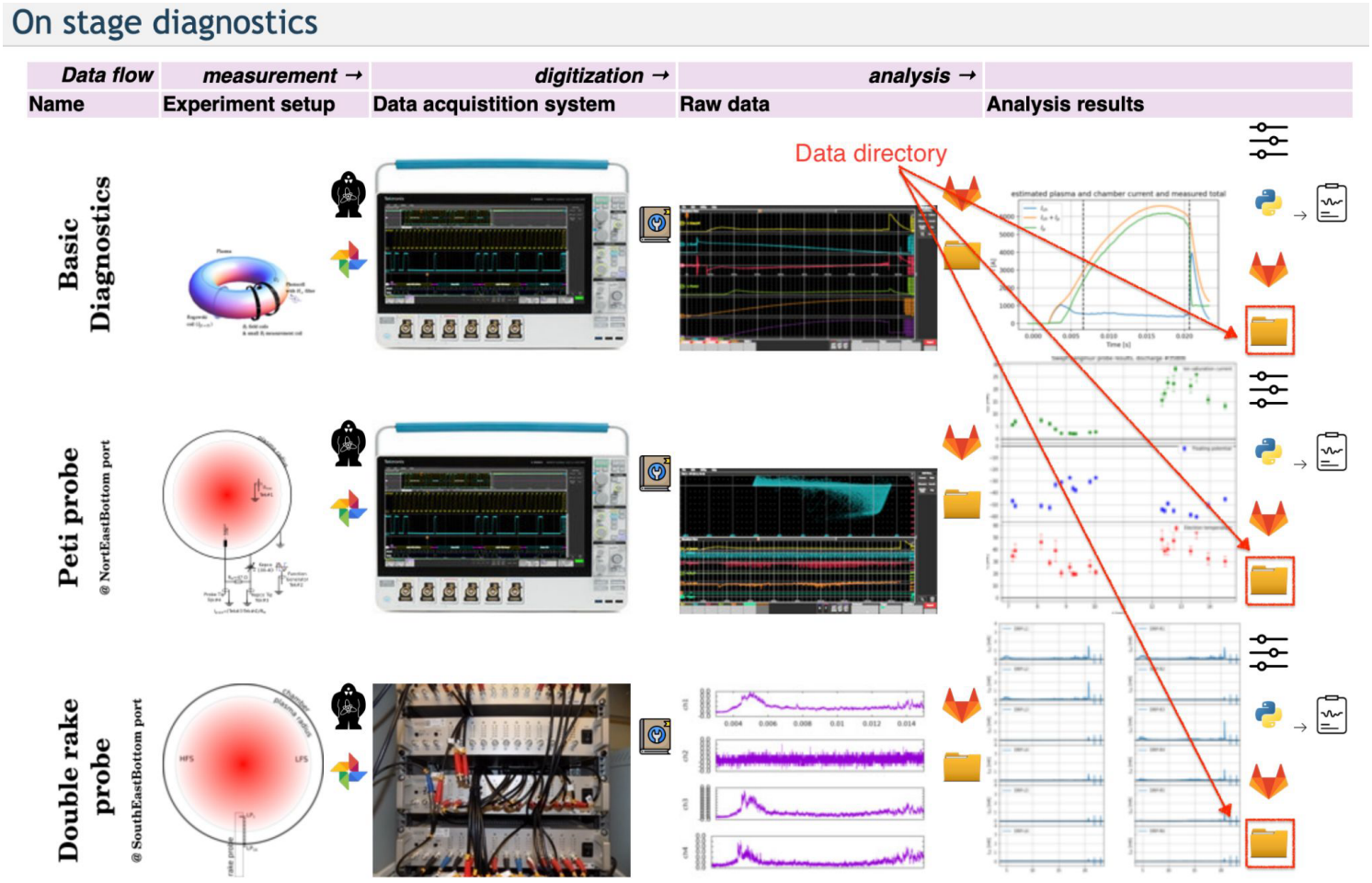
SHOT HOMEPAGE

1. Discharge number
2. Discharge command
3. Technological parameters
4. Plasma parameters
5. Diagnostics

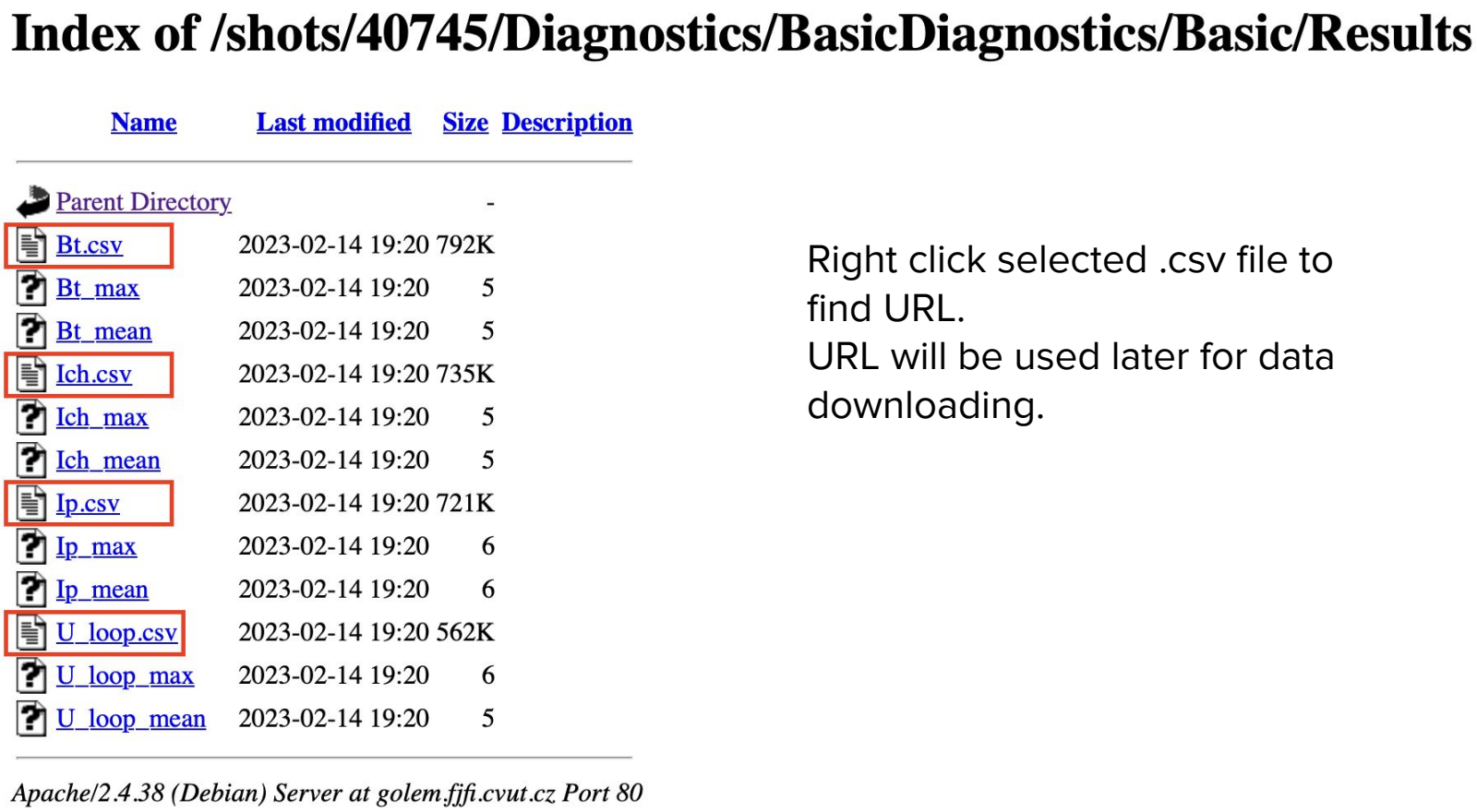
http://golem.fjfi.cvut.cz/shots/40151/



Where to find data on homepage?



Basic Diagnostics data directory



Index of /shots/40745/Diagnostics/BasicDiagnostics/Basic/Results

Name	Last modified	Size	Description
Parent Directory		-	
Bt.csv	2023-02-14 19:20	792K	
Bt_max	2023-02-14 19:20	5	
Bt_mean	2023-02-14 19:20	5	
Ich.csv	2023-02-14 19:20	735K	
Ich_max	2023-02-14 19:20	5	
Ich_mean	2023-02-14 19:20	5	
Ip.csv	2023-02-14 19:20	721K	
Ip_max	2023-02-14 19:20	6	
Ip_mean	2023-02-14 19:20	6	
U_loop.csv	2023-02-14 19:20	562K	
U_loop_max	2023-02-14 19:20	6	
U_loop_mean	2023-02-14 19:20	5	

Apache/2.4.38 (Debian) Server at golem.fjfi.cvut.cz Port 80

Right click selected .csv file to find URL.
URL will be used later for data downloading.

DATA FORMAT

- Data stored in **csv** format (columns separated by "," symbol).
- Several ways to download data:
  - **Manually** download by clicking on it (not recommended, slow, not automatized).
  - Using **wget** command (Linux, Mac users, Windows WSL).
  - Automated downloading using programming languages (**Python**, MATLAB, ...).
- DAS temporal resolution usually 1 µs.
- DAS produces **N** columns x **40000** rows.
- 1st column represents time.
- 2nd column represents measured data.

GOLEM - basic Data Acquisition System DAS

- An example of data representation.
- Csv files can vary in number of columns.
- Time axis units can vary (s or ms).
- Separators can vary.
- Separator must be specified to load the data.
- **Check data before analyzing!**

time [ms]	Bt [T]
9.99335744	0.2602015123779187
9.99435744	0.26022505899274373
9.99535744	0.260248611329229
9.99635744	0.26027216366571426
9.99735744	0.2602957195781975
9.998357440000001	0.2603192726298683
9.99935744	0.2603428235359473
10.0003574	0.2603663749303391
10.0013574	0.26038992583641807
10.0023574	0.26041349033133887
10.003357399999999	0.26043706197829086
10.0043574	0.2604606236123992
10.0053574	0.2604841802400679
10.0063574	0.26050773686773676
10.0073574	0.2605312999322512
10.0083574	0.26055487014879697
10.0093574	0.26057844251093454
10.0103574	0.26060201415788653
10.0113574	0.2606255822288406

WGET

- Wget is used on Linux, Mac, or Windows WSL for data downloading.

Wget is the non-interactive network downloader used to download files from the server.

- For cycles can be used in **bash** to download data from multiple discharges:

```
#!/bin/bash

for shot in {40740..40745}

  do wget "http://golem.fjfi.cvut.cz/shots/$shot/Diagnostics/BasicDiagnostics/Basic/Results/U_loop.csv"

done
```

- The script downloads Bt data from discharges 40740 to 40745.

EXCEL

- Download data using wget and open one after another.
- Open data directly from URL:

How to Import Web Data Into Excel on PC or Mac (with Pictures)

- **Excel is tolerated but not recommended.**
- Usable for easy tasks, not suitable for more complex tasks.
- Disadvantages: difficult to load data, handle it, and process
- Advantages: no need of programming

GNUPLOT

- Command-line driven utility generating two and three dimensional plots.
- Can be used for automatized data visualization.
- Useful and versatile.
- It is not programming language.
- Not very intuitive.
- No graphical interface available.
- The data processing must be done outside GNUPLOT.

GNUPLOT - code example

```
# Create a path to the data
identifier = "U_loop.csv";  # signal name
ShotNo = "40745"  # discharge number
DAS="Diagnostics/BasicDiagnostics/Basic/Results/"  # diagnostics path
baseURL="http://golem.fjfi.cvut.cz/shots/"  # base URL
DataURL= baseURL.ShotNo."/".DAS.identifier  # connect together

set datafile separator ",";  # define separator

# figure setup
set title "Uloop for #".ShotNo;  # title
set xrange [0:25];set xlabel "Time [ms]";set ylabel "U_l [V]"  # labels


# make the plot
plot '< wget -q -O - DataURL' u 1:2 w l t 'Uloop';
```

MATLAB

- Easy to use.
- Great for matrix data manipulation and visualization.
- Predefined functions and complex graphical interface.
- Interprepreted language - can be slow.
- Is not free software.
- Syntax not very similar to other programming languages.

MATLAB - code example

```
% Create a path to the data
identifier = 'U_loop.csv';
ShotNo = '40745';
DAS = 'Diagnostics/BasicDiagnostics/Basic/Results/';
baseURL = 'http://golem.fjfi.cvut.cz/shots/';
DataURL = strcat(baseURL, ShotNo, '/', DAS, identifier);

% Write data from GOLEM server to a local file
websave('data', DataURL);  % download the data from URL to local file called data.csv

% Load data
data = load('data.csv', 's,');  % load data from the local data.csv file

% Plot and save the graph
figure;
plot(data(:,1), data(:,2), '.') ;
title(strcat('U loop for #', ShotNo));
xlabel('time [ms]')
ylabel('U_loop [V]')
```

OCTAVE

- Similar syntax to MATLAB.
- Free software.
- Both GUI and no-GUI interface.
- No all of the fancy libraries and packages MATLAB offers.
- Not a general purpose programming language.
- Interpreted language => slow.

OCTAVE - code example

```
% Create a path to the data
identifier = 'U_loop.csv';
ShotNo = '40745';
DAS = 'Diagnostics/BasicDiagnostics/Basic/Results/';
baseURL = 'http://golem.fjfi.cvut.cz/shots/';
DataURL = strcat(baseURL, ShotNo, '/', DAS, identifier);

% Write data from GOLEM server to a local file
urlwrite(DataURL, 'data_octave');  % download the data from URL to local file called data

% Load data
data = load('data_octave', 's,');  % load data from the local data.csv file

% Plot and save the graph
figure;
plot(data(:,1), data(:,2), '.') ;
title(strcat('U loop for #', ShotNo));
xlabel('time [ms]')
ylabel('U_loop [V]')
```

PYTHON - recommended programming language

- One of the best programming languages to be used generally.
- Offers simple syntax, powerful modules.
- Relatively easy to learn, some parts of syntax similar to MATLAB (matplotlib).
- Free to use.
- Can be very fast when using correctly.
- Jupyter Notebook - great IDE allowing divide the code into cells.
- Almost no disadvantages :)

PYTHON - IDEs to use

- Script in .py file - *python3 script.py* **-** not optimal.
- **VSCode / Cursor**
- pyCharm
- SPYDER
- **Jupyter Notebook - Anaconda3**
  - Advantages: all in one place, easy to convert (HTML, PDF, ...), easy to share, interactive, code divided into cells, markdown included, easy to use custom python environment, great for simpler data processing tasks.
  - Disadvantages: not best for long projects, less security, no code asistation.

https://docs.anaconda.com/anaconda/install/index.html

jupyterhub GOLEM data processing Last Checkpoint: před dnem (unsaved changes)

Logout Control Panel

File Edit View Insert Cell Kernel Widgets Help

Not Trusted | Python 3.9 [2021.11]

Run Code

Comments

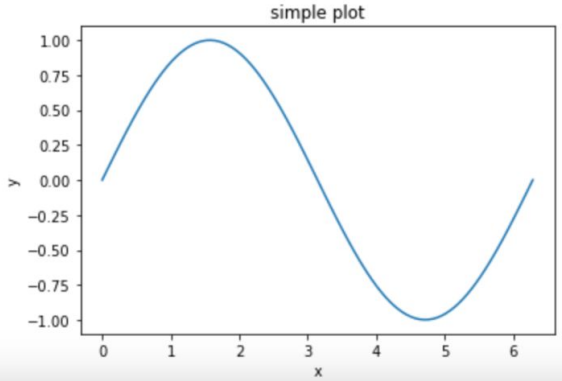
- comments can be written using markdown language
- the best way to comment your code
- equations can be written using LaTex - $R = \frac{U}{I}$

In [10]:
```
# Module imports
import numpy as np
import matplotlib.pyplot as plt
import pandas as pd
```

In [11]:
```
x = np.linspace(0, 2 * np.pi, 100)
y = np.sin(x)
```

In [12]:
```
plt.figure()
plt.plot(x, y)
plt.title('simple plot')
plt.xlabel('x')
plt.ylabel('y')
```

Out[12]: Text(0, 0.5, 'y')



Basic operations

In [151]:
```
# anything after '#' is a comment
a = 5       # assign value 5 (integer) to name 'a'
b = a * 2.5 - 3.7 + 9.7 / 3 + 2**4    # automatic casting to float, standard math operators  (** is exponentiat
b           # last (unassigned) value in cell is returned and printed
```

Out[151]:
```
28.03333333333333
```

In [153]:
```
description = 'b is now:'  # strings are delimited by ''  or ""
print(description, b)      # the print function (called with 'func()') prints all arguments
```

```
b is now: 28.03333333333333
```

In [154]:
```
def radius(x, y, x0=0, y0=0):  # 'def' starts a function definition, arguments can have default values arg=valu
    """Return radius of point [x,y] from [x0,y0]"""

    r = (x-x0)**2 + (y-y0)**2  # commands within the function are indented by 4 spaces
    return r**0.5    # this is the value returned by the function
```

In [155]:
```
vec = [1, 5, 6, 7]  # a list of values in square brackets
```

In [158]:
```
for v in vec:  # iterate over elements in list
    r = radius(v, y=1)   # parameters specified by position or name=value
    print('r = ', round(r, 2))  # print value rounded to 2 decimal points
```

```
r =  1.41
r =  5.1
r =  6.08
r =  7.07
```

In [157]:
```
rs = [radius(v, 5) for v in range(10)]   # list generator comprehension using range(n) -> [0, 1, ..., n-1]
rs
```

Out[157]:
```
[5.0,
 5.0990195135927845,
 5.385164807134504,
 5.830951894845301,
 6.4031242374328485,
 7.0710678118654755,
 7.810249675906654,
 8.602325267042627,
 9.433981132056603,
 10.295630140987]
```

PYTHON - collections

- **List:**
  - Defined by square bracelets.
  - A collection of ordered data, mutable.
- Tuple:
  - Defined by round bracelets.
  - Ordered collection of data, immutable, higher performance, used as indices for dicts, have defined shape.
- Dictionary:
  - Defined by curly bracelets.
  - Unordered collection of data that stores data in key-value pair.

In [171]:
```
# array
my_array = [1, 2, 3, 4, 5]
print(my_array)
print('value of my_array on third position: ', my_array[2])
```

```
[1, 2, 3, 4, 5]
value of my_array on third position:  3
```

In [172]:
```
# tuple
my_tuple = (1, 2, 3, 4, 5)
print(my_tuple)
print('value of my_tuple on second position: ', my_tuple[1])
```

```
(1, 2, 3, 4, 5)
value of my_tuple on second position:  2
```

In [173]:
```
# dictionary
my_dictianory = {'A': [1, 2 ,3], 'B': 'test', 'C': 5.234}
print(my_dictianory)
print('value of my dictionary in key A: ', my_dictianory['A'])
```

```
{'A': [1, 2, 3], 'B': 'test', 'C': 5.234}
value of my dictionary in key A:  [1, 2, 3]
```

PYTHON - working with strings

- An 'f' strings can be used for inserting variables into strings.
- Insert 'f' letter at the beginning of the string.
- Use curly braces '{', '}' and insert the variable inside.
- The string will be concatenated.

In [76]:
```
1 shot_no = '40745'
2 identifier = 'U_loop.csv'
3 url = f'http://golem.fjfi.cvut.cz/shots/{shot_no}/Diagnostics/BasicDiagnostics/Basic/Results/{identifier}'
4
5 print(url)
```

```
http://golem.fjfi.cvut.cz/shots/40745/Diagnostics/BasicDiagnostics/Basic/Results/U_loop.csv
```

PYTHON - modules

- Numpy
  - Multi-dimensional arrays and matrices equipped with high-level mathematical operations.
  - In our case is used for basic data manipulation.
- Matplotlib
  - Plotting library used for creating static, animated, or interactive visualizations.
  - In our case is used for basic or complex data plotting.
- Pandas
  - Module used for data manipulation and analysis in form of data structured (various tables).
  - In our case is used for data manipulation in form of data frames.

PYTHON - numpy

In [10]:
```
import numpy
```

Important numpy functions

array, linspace, arange, empty, eye, zeros, ones, load, loadtxt, save, random.rand

In [15]:
```
A = [1, 2, 3, 4, 5]  # standard Python array
A_np = np.array([1, 2, 3, 4, 5])

print('Standart Python list type: ', type(A))
print('Numpy Python list type: ', type(A_np))
```

```
Standart Python list type:  <class 'list'>
Numpy Python list type:  <class 'numpy.ndarray'>
```

In [17]:
```
matrix = np.random.rand(10, 10)  # create matrix 10x10 filled by random numbers
```

In [19]:
```
print(matrix[:, 0])  # indexing the first column of the matrix
```

```
[0.70609552 0.76054409 0.46304194 0.95361304 0.16183893 0.02872066
 0.4457452  0.35962072 0.52477787 0.70726263]
```

In [26]:
```
# Basic operations
B = matrix + 2  # add 2 to each element of matrix
C = matrix * B  # multiply each element of matrix by element of B
```

PYTHON - numpy

Loading data from server using numpy

In [33]:
```
# Import urlopen from urllib.request library
# The libraty is used for opening data on servers
from urllib.request import urlopen
```

In [35]:
```
# Define path to the data
url = 'http://golem.fjfi.cvut.cz/shots/40745/Diagnostics/BasicDiagnostics/Basic/Results/U_loop.csv'

# Use urlopen to open the URL, the load opened URL with np.loadtxt
# Delimiter must be defined!
U_loop = np.loadtxt(urlopen(url), delimiter = ',')
```

In [38]:
```
# Shape of the data can be displayed using shape function
# First column is time axis, second the loop voltage
print('Data shape: ', U_loop.shape)
```

```
Data shape:  (24000, 2)
```

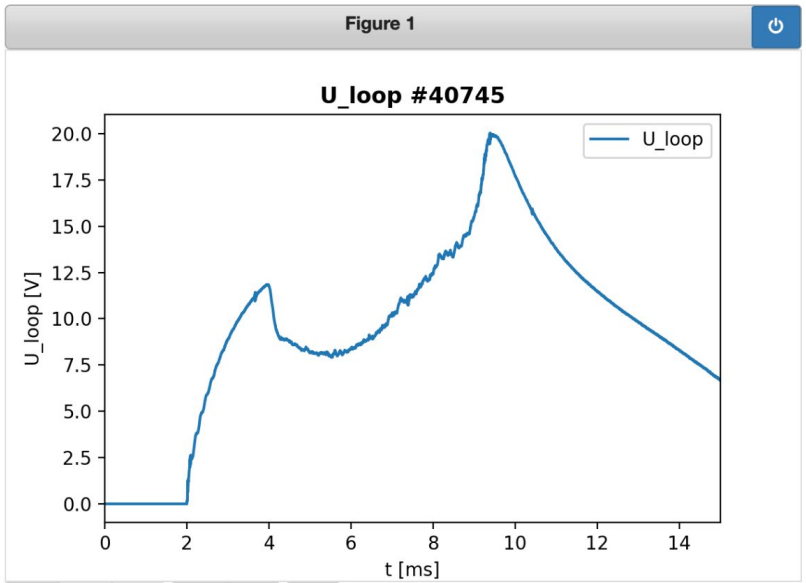
In [40]:
```
# Optional step (not recommended to do this), better to use in one variable U_loop
t = U_loop[:, 0]  # this is how to load time axis into variable
U_loop_data = U_loop[:, 1]  # this is how to load data into variable
```

Python - matplotlib

Data visualization

In [49]:
```
# Import matplotlib library for data visualization
import matplotlib.pyplot as plt
# Highly recommended to use notebook format - allows interactive plots
%matplotlib notebook
```

In [58]:
```
plt.figure(figsize = (6, 4))  # create a figure first
plt.plot(U_loop[:, 0], U_loop[:, 1], label = 'U_loop')  # plot the data (time and data columns), create label
plt.title('U_loop #40745', fontweight = 'bold')  # create title
plt.xlabel('t [ms]')  # create x label
plt.ylabel('U_loop [V]')  # create y label
plt.xlim(0, 15)  # adjust x-axis range
plt.legend()
```



Python - pandas

Using pandas

In [61]:
```
# Import pandas module
import pandas as pd
```

In [64]:
```
url = 'http://golem.fjfi.cvut.cz/shots/40745/Diagnostics/BasicDiagnostics/Basic/Results/U_loop.csv'
# Easy way to load the data into pandas DataFrame
U_loop_pd = pd.read_csv(url, names = ['t', 'data'])
```

In [66]:
```
U_loop_pd.head(10)
```

Out[66]:

	t	data
0	-0.719643	0.0
1	-0.718643	0.0
2	-0.717643	0.0
3	-0.716643	0.0
4	-0.715643	0.0
5	-0.714643	0.0
6	-0.713643	0.0
7	-0.712643	0.0
8	-0.711643	0.0
9	-0.710643	0.0

PYTHON - pandas

In [67]:
```
1 url = 'http://golem.fjfi.cvut.cz/shots/40745/Diagnostics/BasicDiagnostics/Basic/Results/U_loop.csv'
2 # Easy way to load the data into pandas DataFrame
3 U_loop_pd = pd.read_csv(url, names = ['t', 'data'], index_col = 't')
```

In [68]:
```
1 U_loop_pd.head(10)
```

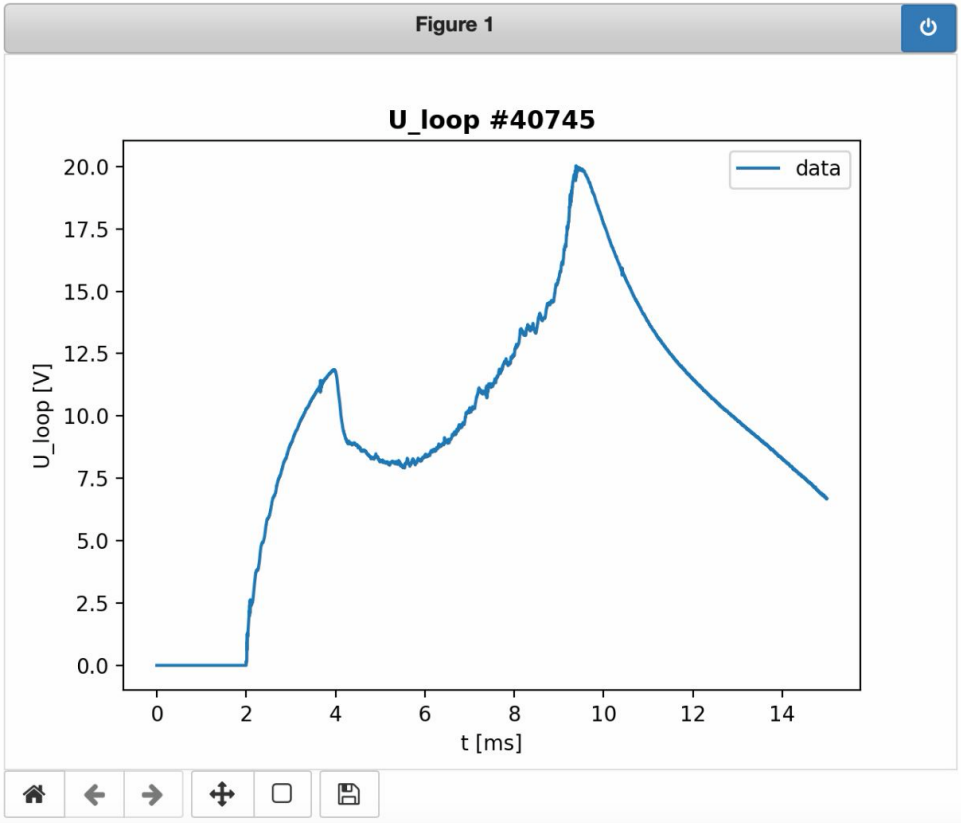
Out[68]:

	data
t	
-0.719643	0.0
-0.718643	0.0
-0.717643	0.0
-0.716643	0.0
-0.715643	0.0
-0.714643	0.0
-0.713643	0.0
-0.712643	0.0
-0.711643	0.0
-0.710643	0.0

PYTHON - pandas

In [75]:

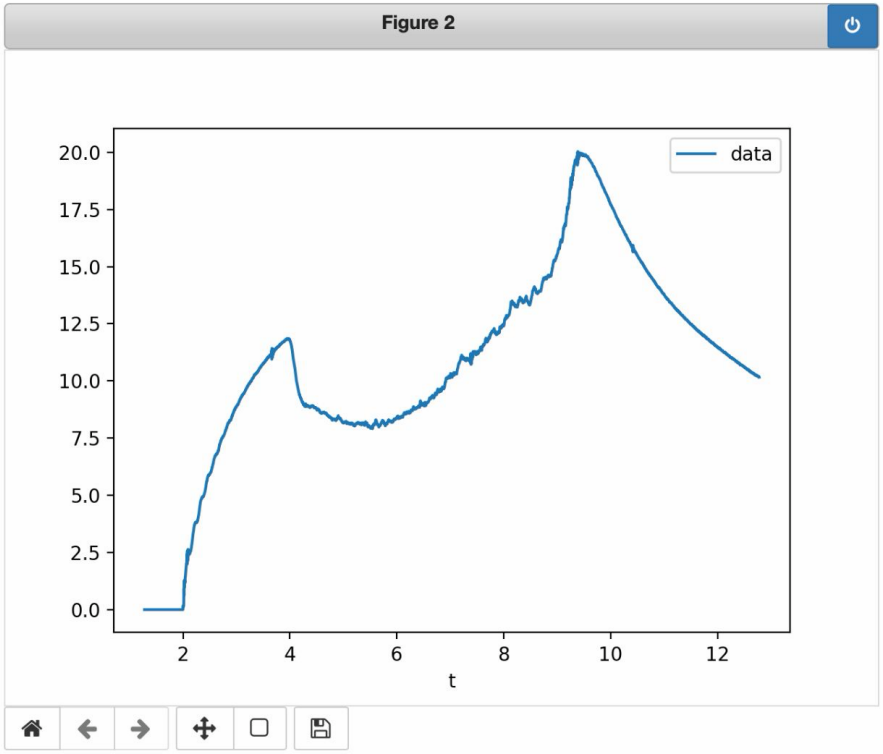
```
1 U_loop_pd[0: 15].plot()  # the way how to plot in pandas, because time is index, [] can be used for slicing data
2 plt.title('U_loop #40745', fontweight = 'bold')  # create title
3 plt.xlabel('t [ms]')  # create x label
4 plt.ylabel('U_loop [V]')  # create y label
5 plt.legend()
```



PYTHON - selecting data in pandas

In [80]:
```
# How to select column from a DataFrame (not recomended):
t = U_loop_pd.index
U_loop_pd_data = U_loop_pd.data
```

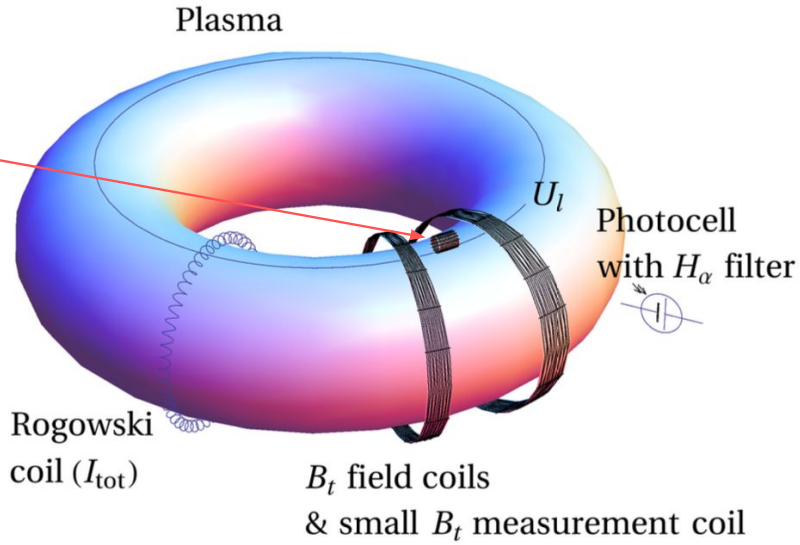
In [85]:
```
# Indexing by index (from index 2000 to index 13500)
U_loop_pd.iloc[2000: 13500].plot()
```



Simple example of toroidal magnetic field determination

Toroidal magnetic field determination

- Toroidal magnetic field measured by small coil.
- Its axis parallel to the magnetic field.
- Measures the time derivative of the toroidal magnetic field.
- Toroidal magnetic field determined based on the Faraday's law.



$$B_t(t) = C_{B_t} \int_0^t U_{B_t}(\tau) d\tau$$

Loading the data

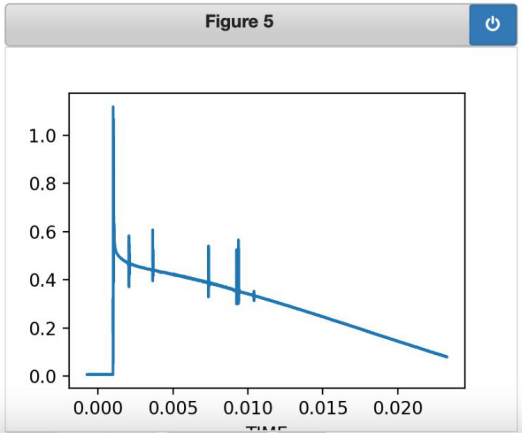
In [99]:
```
1 url = 'http://golem.fjfi.cvut.cz/shots/40745/Diagnostics/BasicDiagnostics/Basic/DAS_raw_data_dir/TektrMSO56_ALL.
2 # Load all basic diagnostics signal into pandas DataFrame
3 data_basic_diag = pd.read_csv(url, skiprows = 10, index_col = 'TIME')
```

In [101]:
```
1 # Show loaded data. Measured signals corresponds to CH1, .. CH6
2 data_basic_diag.head(5)
```

Out[101]:

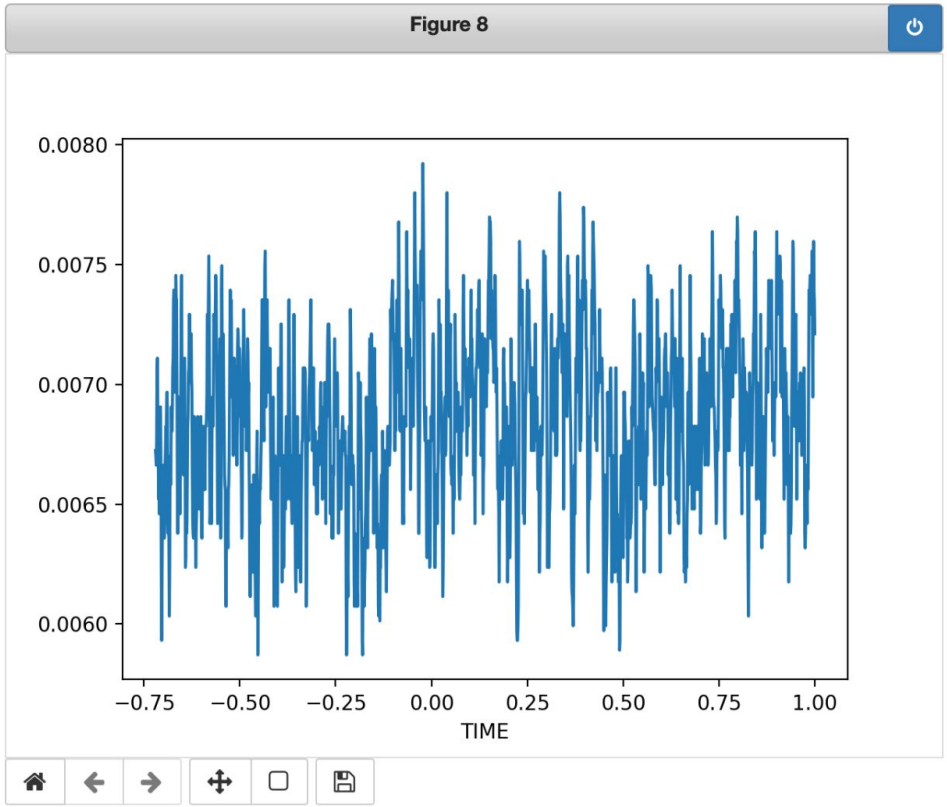
TIME	CH1	CH2	CH3	CH4	CH5	CH6	Unnamed: 7	TIME.1	MATH1	Unnamed: 10	TIME.2	MATH2
-0.000720	0.138281	0.006723	-0.001734	0.008125	0.043906	0.046289	NaN	-0.000720	4.734645e-07	NaN	-0.000720	-14.246607
-0.000719	0.137500	0.006703	-0.000703	0.008000	0.043906	0.043828	NaN	-0.000719	9.462137e-07	NaN	-0.000719	-14.159606
-0.000718	0.128125	0.006663	0.000484	0.008000	0.044687	0.042656	NaN	-0.000718	1.416817e-06	NaN	-0.000718	-13.192532
-0.000717	0.119531	0.006764	-0.000266	0.007938	0.045000	0.040664	NaN	-0.000717	1.889567e-06	NaN	-0.000717	-12.307158
-0.000716	0.130469	0.007048	-0.002750	0.008000	0.046875	0.039023	NaN	-0.000716	2.375905e-06	NaN	-0.000716	-13.426744

In [115]:
```
1 plt.figure(figsize = (4, 3))
2 data_basic_diag['CH2'].plot()  # plot signal measured by Bt coil
```



Removing offset I

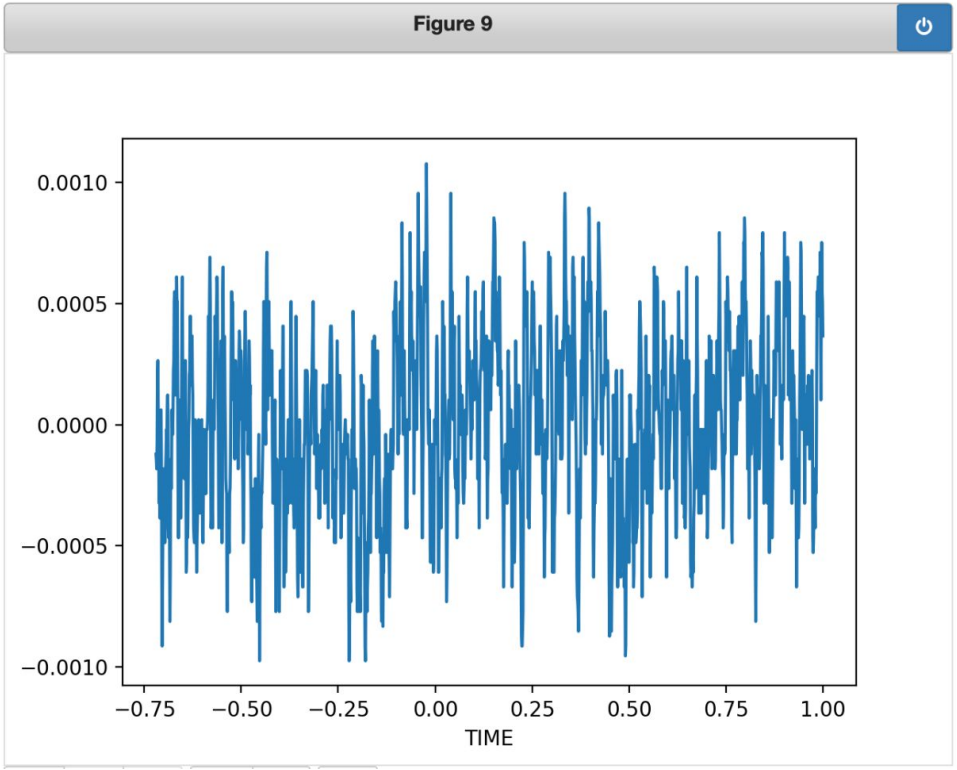
In [131]:
```
# Signal is not starting at 0! Must be shifter to zero to calculate integral corectly!
plt.figure()
data_basic_diag.loc[-1:1]['CH2'].plot()
```



Removing offset II

In [132]:
```
data_basic_diag['CH2'] = data_basic_diag['CH2'] - data_basic_diag.loc[-1:1]['CH2'].mean()
```

In [133]:
```
# Signal is not starting at 0! Must be shifter to zero to calculate integral corectly!
plt.figure()
data_basic_diag.loc[-1:1]['CH2'].plot()
```

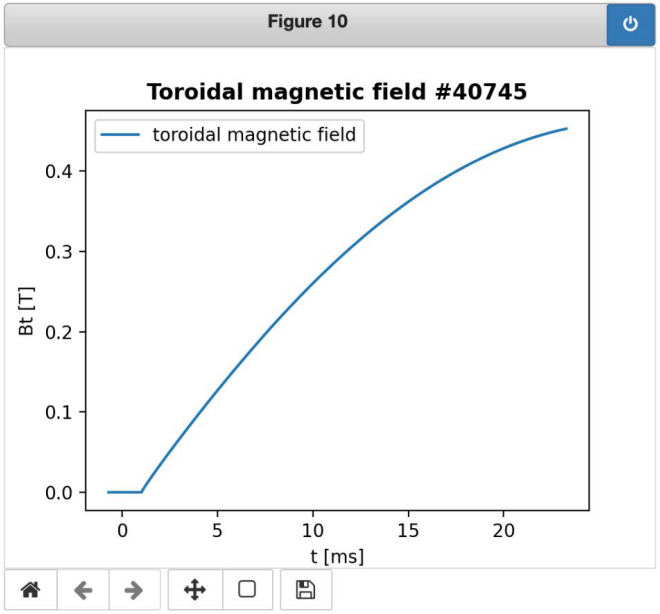


Integration

In [134]:
```
# Import module for numerical integration
from scipy import integrate
```

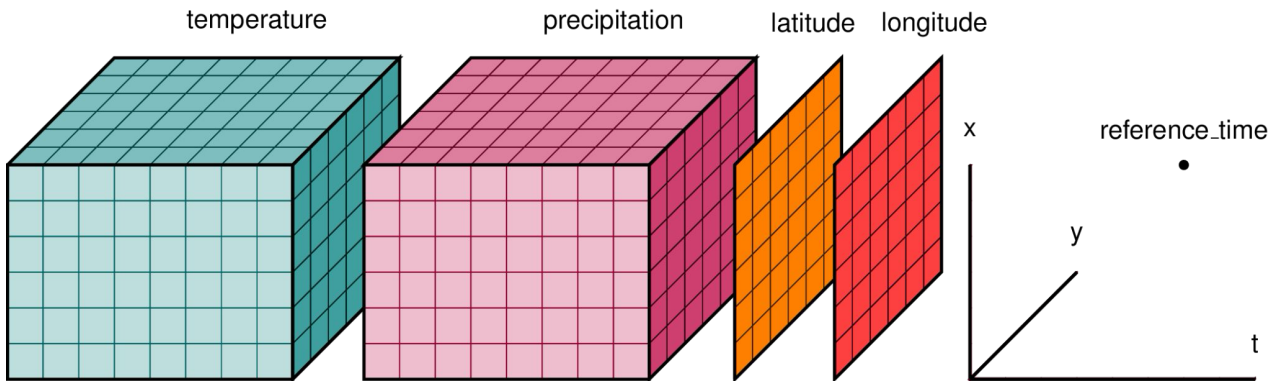
In [146]:
```
Bt = pd.Series(integrate.cumtrapz(data_basic_diag['CH2'], x=data_basic_diag.index/1000, initial=0) * 70.42,
               name = 'Bt', index = data_basic_diag.index)
```

In [150]:
```
plt.figure(figsize = (5, 4))
Bt.plot(label = 'toroidal magnetic field')
plt.xlabel('t [ms]')
plt.ylabel('Bt [T]')
plt.title('Toroidal magnetic field #40745', fontweight = 'bold')
plt.legend()
```



PYTHON - xarray

- Multidimensional arrays - **DataArray** or **Dataset**.
- More intuitive, more concise, and less error-prone.
- Introduces labels in form of dimensions, coordinates, and attributes.
- Example: **dimensions** (x, y, t), **coordinates** (latitude (x), longitude (y)), **data_var** (temperature(x, y, t), precipitation(x,y,t))



PYTHON - xarray example

```
[16]: ds = xr.open_dataset('./tutorial-data/sst/NOAA_NCDC_ERSST_v3b_SST-1960.nc')
      ds
```

[16]: xarray.Dataset

▸ Dimensions: (**lat**: 89, **lon**: 180, **time**: 12)

▾ Coordinates:

lat	(lat)	float32	-88.0 -86.0 -84.0 ... 86.0 88.0
lon	(lon)	float32	0.0 2.0 4.0 ... 354.0 356.0 358.0
time	(time)	datetime64[ns]	1960-01-15 ... 1960-12-15

▾ Data variables:

sst	(time, lat, lon)	float32	...

▾ Attributes:

Conventions :	IRIDL
source :	https://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCDC/.ERSST/.version3b/.sst/
history :	extracted and cleaned by Ryan Abernathey for Research Computing in Earth Science

Best Practises

- Document your code - make comments.
- Use one statement per line (do not use print(“A”); print(“B”); ...).
- Code indentation (proper tabs, spaces, etc).
- Do not repeat yourself
- Use a Proper Naming Convention.
- Avoid magic numbers.

CONCLUSION

- Conversion of the data to useful information.
- Almost all experiments raw data has to be analyzed.
- Data can be processed using several programming languages:
  - **Python,** MATLAB, Octave, GNUPLOT, or Excel.
- Python is currently the best programming language for data analysis.
- Follow best practices.
- The most important - enjoy the process of data analysis :)