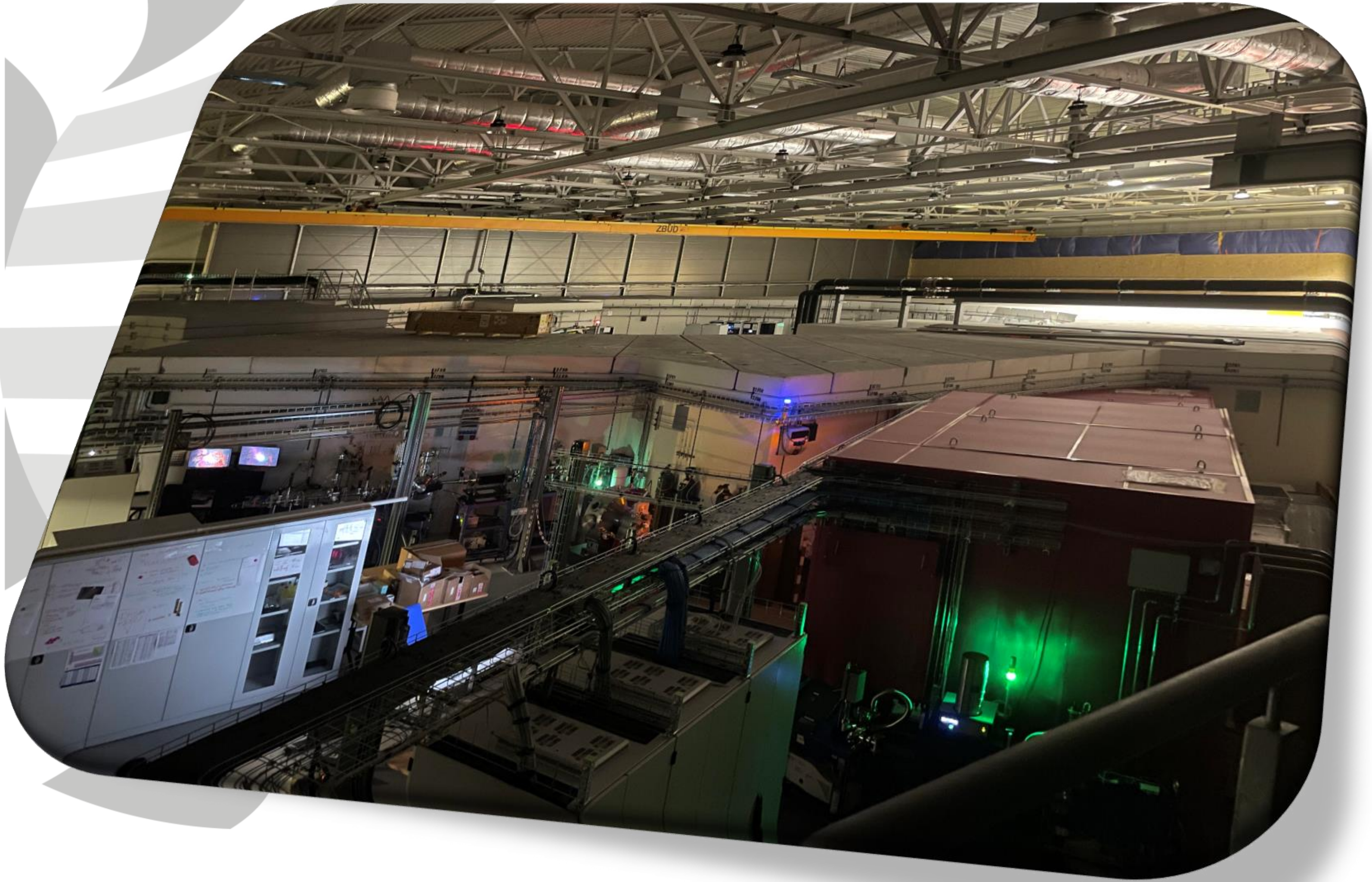
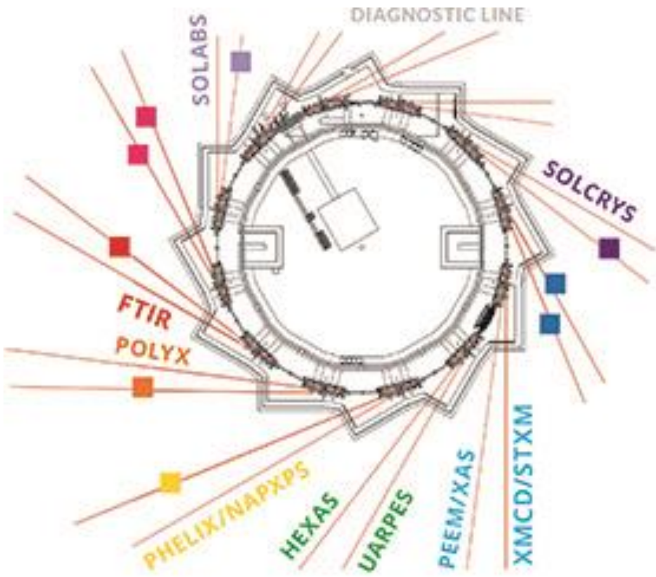




SOLARIS
CENTRE

SOLARIS CENTRE

SOLARIS synchrotron. Status and planed developments.

Kraków, 20.02.2023

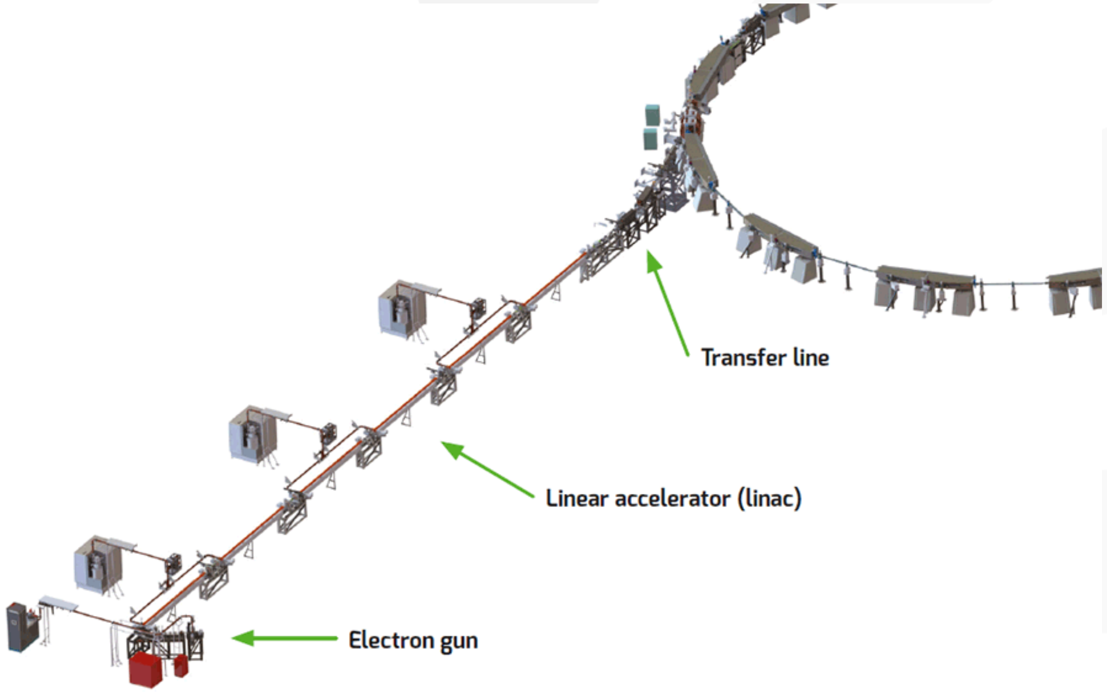
Jacek Biernat, Roman Panaś
SOLARIS National Synchrotron Radiation Centre

Contents

- Introduction into SOLARIS and synchrotron radiation
- Applications of synchrotron radiation
- Present and the future of SOLARIS
- Introduction and results of typical beam diagnostics
- Machine Learning, Time Series analysis, Forecasting/ (possibly anomalous behavior detection) with neural networks
- Conclusions

The Solaris accelerator facility – linear booster accelerator

Delivered injection energy [MeV]	**~550**
Single bunch charge [nC]	**0,1**
Beam current [mA]	**20-30**
Normalized emittance (rms) horizontal /vertical [mm mRad]	**3,111/2,175**
Energy spread at the injector exit [keV]	**400**
Length of a single electron bunch [ps]	**14**



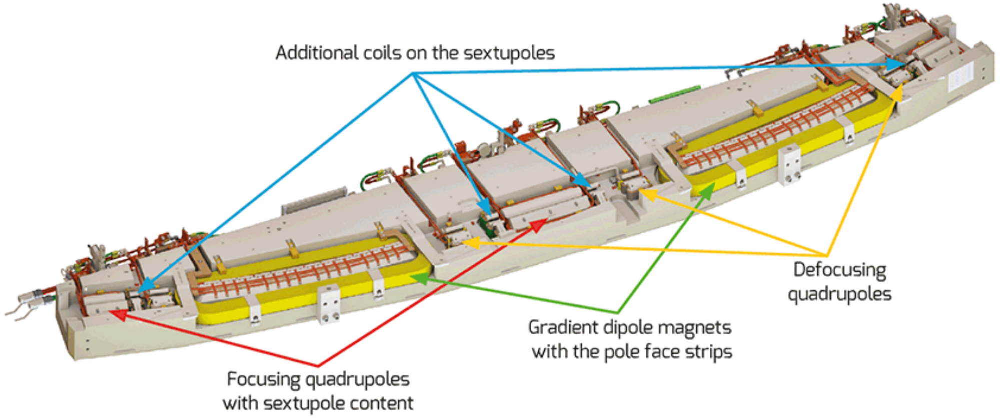
The thermionic electron radio frequency (RF) gun is a 3 GHz RF cavity. The source of the electrons is BaO. The pulsed electric field bunches an electron beam and accelerates it up to 2.8 MeV.

The linear accelerator (linac) consists of six 5 m long S-band travelling wave accelerating structures combined in three accelerating units. Each accelerating unit contains one SLED (SLAC Energy Double`r) cavity and **two linac** structures and is powered by an RF amplifier. Linac is 40 m long and delivers maximum beam energy of 600 MeV.

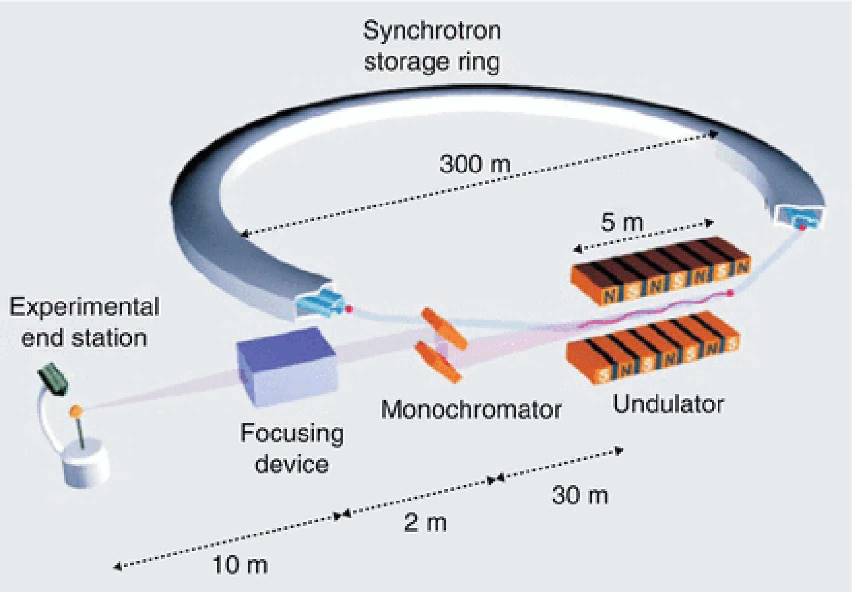
The transfer line composed of dipoles with a total bend angle of 27 degrees, which bend the beam in the vertical plane, as well as six focusing quadrupoles. The last element is a septum magnet, which connects the injector with the storage ring.

The Solaris accelerator facility – electron storage ring

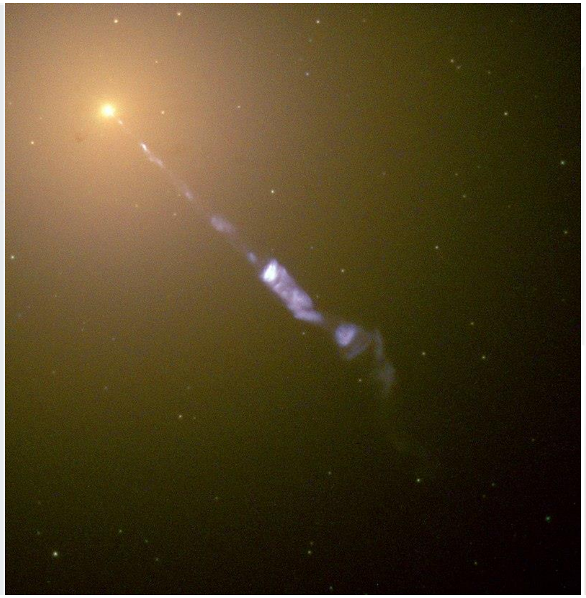
Energy	1.5 GeV
Max. current	500 mA
Circumference	96 m
Main RF frequency	99,93 MHz
Max. number of circulating bunches	32
Horizontal emittance (without insertion devices)	6 nm rad
Electron beam size (straight section centre) σ_x, σ_y	184 µm, 13 µm
Electron beam size (dipole centre) σ_x, σ_y	44 µm, 30 µm
Max. number of insertion devices	10
Momentum compaction	3.055×10^{-3}
Total lifetime of electrons	13 h



Synchrotron Radiation

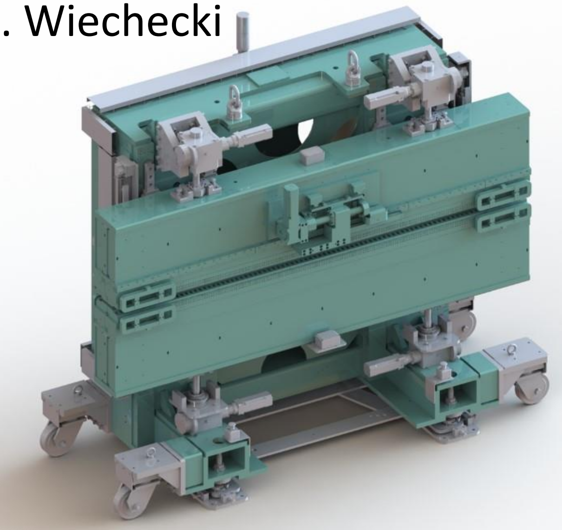


DOI: 10.1007/978-94-017-9780-1_100927



Known phenomena in nature for example radiation emitted form jets.

J. Wiechecki



Schematic view of a Undulator setup, presenting the jaws and the magnets within them

$$P_\gamma = \frac{1}{6\pi\varepsilon_0}\frac{q^2a^2}{c^3}\gamma^4,$$

where

- ε_0 is the vacuum permittivity,
- q is the particle charge,
- a is the magnitude of the acceleration,
- c is the speed of light,
- γ is the Lorentz factor.

Advantages:

→ High brilliance and flux (combined with high collimation)
→ Wavelength tunability (depending on source & optics)
→ Beam size tunability (depending on source & optics)
→ (Partially) coherent radiation
→ Polarization (linear, elliptical or circular)
→ Time structure

Synchrotron radiation application (selected examples) + electron beam physics

Spectroscopy

X-ray absorption

X-ray fluorescence

IR radiation absorption

Photoelectron emission

Magnetic dichroism

Microscopy

Electron microscopy

Scanning emission microscopy

Photoelectron microscopy

Diffraction

X-ray crystallography

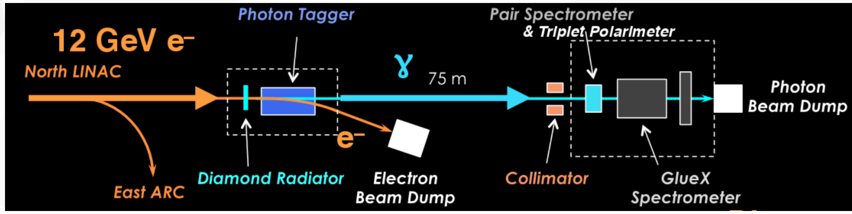
X-ray tomography

Low angle scattering

Electron diffraction

Also, in nuclear physics: Jefferson Lab

- Photonuclear reactions (JLab Hall-D experiment)

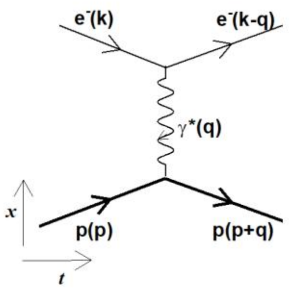


- photo activation of different nuclide

10.1002/9780470027318.a6211.pub2

- e^- p at low energy 600 MeV: double at **SOLARIS**

SOLARIS NARODOWE CENTRUM PROMIENIOWANIA SYNCHROTRONOWEGO



Cross section measurement for low energy is missing!

https://irfu.cea.fr/en/Phocea/Vie_des_labos/Ast/ast.php?t=fait_marquant&id_ast=4636

Photon Activation

Table 1 Analytically usable photonuclear reactions; a selection

Element	Reaction	Half-life	E_{Ph} (keV)	S^a (µg)
C	$^{12}C(\gamma, n)^{11}C$	20 min	511[b]	0.1
N	$^{14}N(\gamma, n)^{13}N$	9.96 min	511[b]	0.02
O	$^{16}O(\gamma, n)^{15}O$	2 min	511[b]	0.05
F	$^{19}F(\gamma, n)^{18}F$	110 min	511[b]	0.001
Na	$^{23}Na(\gamma, n)^{22}Na$	2.6 a•	1275	15
Cl	$^{35}Cl(\gamma, n)^{34m}Cl$	32 min	146	0.005
Ca	$^{44}Ca(\gamma, p)^{43}K$	22.2 h	372	0.5
Cr	$^{52}Cr(\gamma, n)^{51}Cr$	27.8 days	320	0.3
Ni	$^{58}Ni(\gamma, n)^{57}Ni$	36 h	1379	0.06
As	$^{75}As(\gamma, n)^{74}As$	17.77 days	596	0.05
Zr	$^{90}Zr(\gamma, n)^{89}Zr$	78.4 h	909	0.03
Cd	$^{116}Cd(\gamma, n)^{115}Cd$ $^{115}Cd(\beta^-)^{115m}In$	53.38 h	336	0.05
Sb	$^{123}Sb(\gamma, n)^{122}Sb$	2.7 days	564	0.01
I	$^{127}I(\gamma, n)^{126}I$	12.8 days	388	0.04
Ce	$^{140}Ce(\gamma, n)^{139}Ce$	137.5 days	166	0.06
Tl	$^{203}Tl(\gamma, n)^{202}Tl$	12.2 days	440	0.04
Pb	$^{204}Pb(\gamma, n)^{203}Pb$	52.1 h	279	0.1
Bi	$^{209}Bi(\gamma, 3n)^{206}Bi$	6.24 days	804	10
U	$^{238}U(\gamma, n)^{237}U$	6.75 days	59.5[c]	0.001

[a] Sensitivity at standard conditions (Ref. 7, p. 305ff).
[b] To be measured after radiochemical separation.
[c] To be measured with a low-energy photon (LEP) spectrometer (Section 3.1.3).

Example reactions, at the moment no activity in this direction

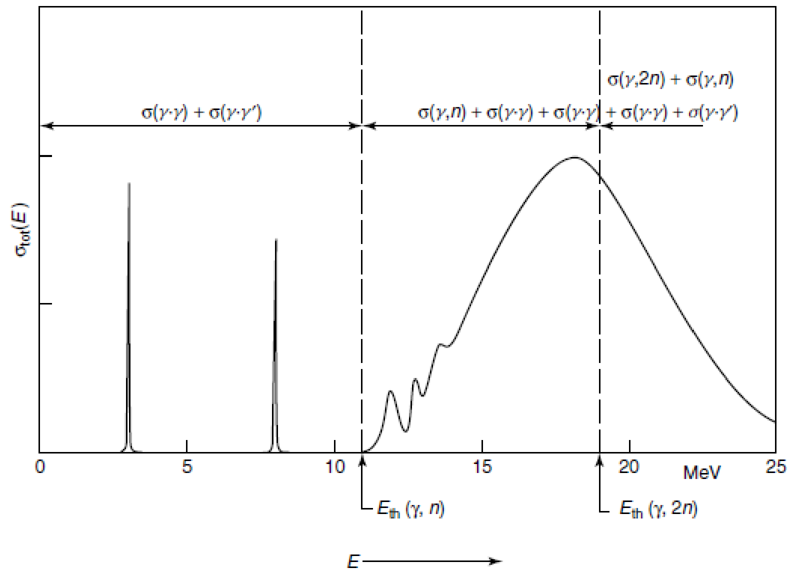
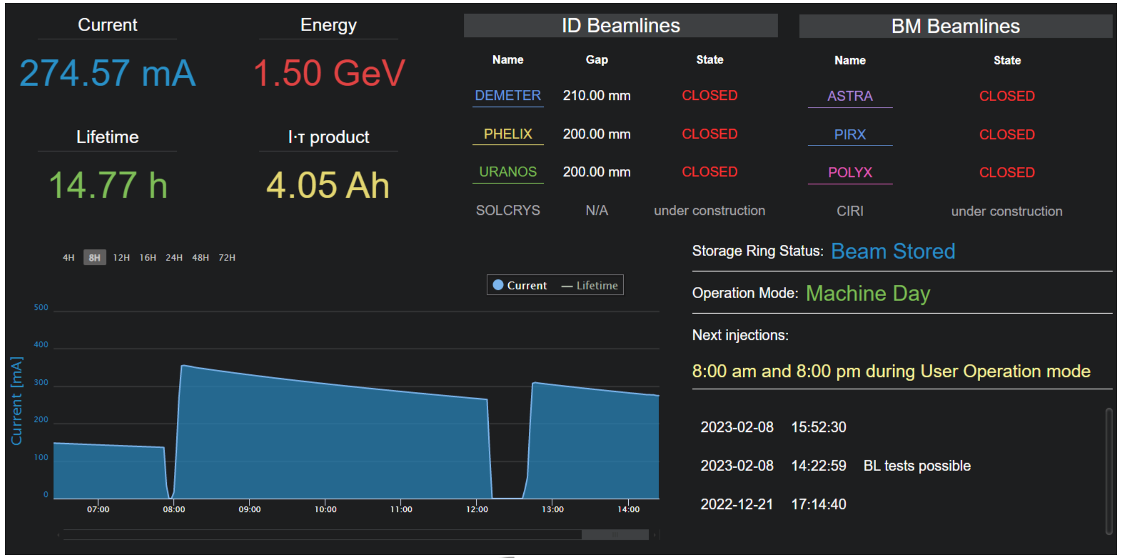


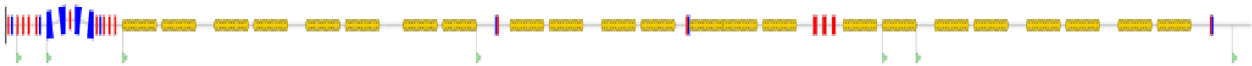
Figure 2 Total (γ, γ') and (γ, xn) absorption cross section, schematically. σ_{tot}, total photon absorption cross section and E_{th}, threshold energy. (Reproduced from Verlag Walter de Gruyter GmbH & Co. KG by permission of Segebade et al.[7]).

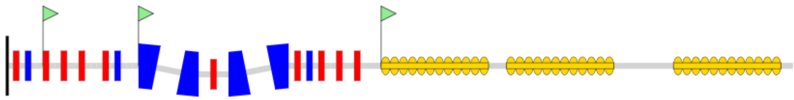
Current Status and what will be… in the near future

- **<u>Decay mode of operation</u>**
- Max energy of 1.5 GeV
- Slow orbit correction
- 6 experimental beam lines in operation
- 3 undulators in operation
- A set of diagnostic tools based on python
- Maximum of 32 bunches, single bunch mode possible



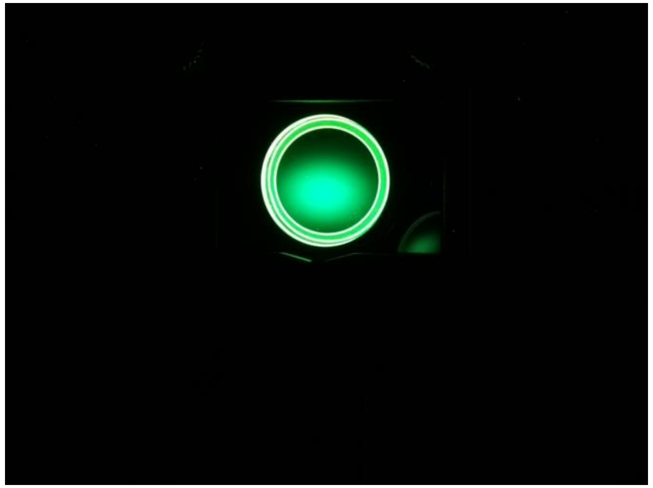
- Orbit tuning and response matrix calculation based on **real time ML**
- Accelerator subsystem diagnostic tools based on **time series** analysis/ **anomaly detection,** possible forecasting
- Real time diagnostic tool connected with **tango** and **mySQL hdb++** database
- GPU utilization for calculation speed up
- Two applications pending: **NCN Opus (done)**, **NCBIR Lider (in progress)**
- Small GPU cluster, possibly 3-4 NVIDIA based GPU (QUADRO ~ 32 GB ram per unit)
- **Top-up mode** (constant filling) and liniac upgrade up to 1.5 GeV

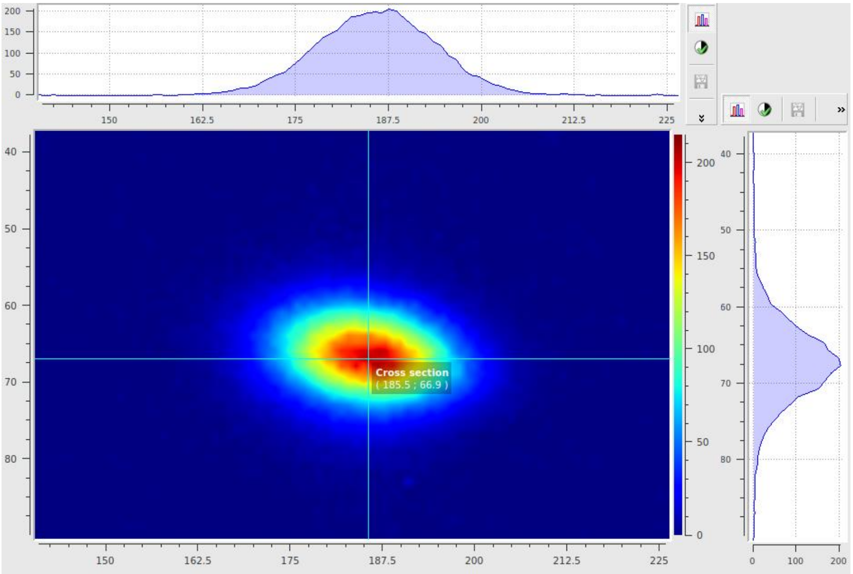




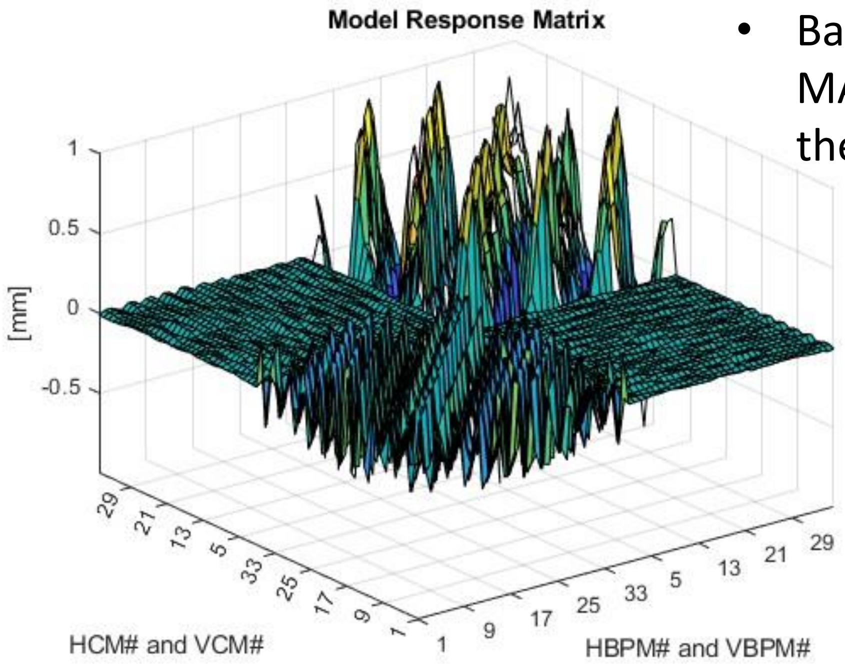
Current status of the complex

- We are back for operation (user beamline commissioning starts in a week)
- The ring operates now with E_{beam} = 1.5 GeV and around 400 mA of current





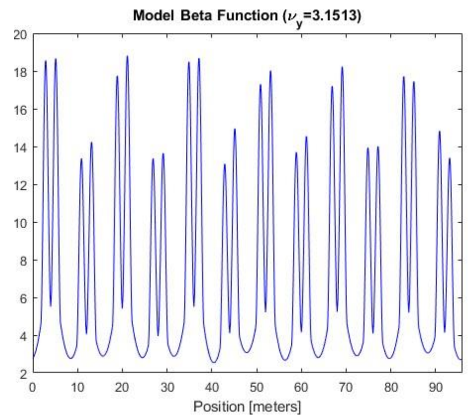
Current status of measurements done with LOCO

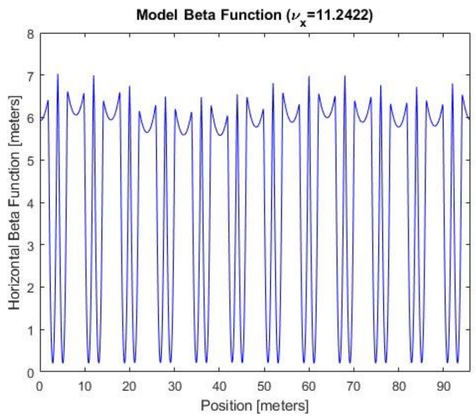


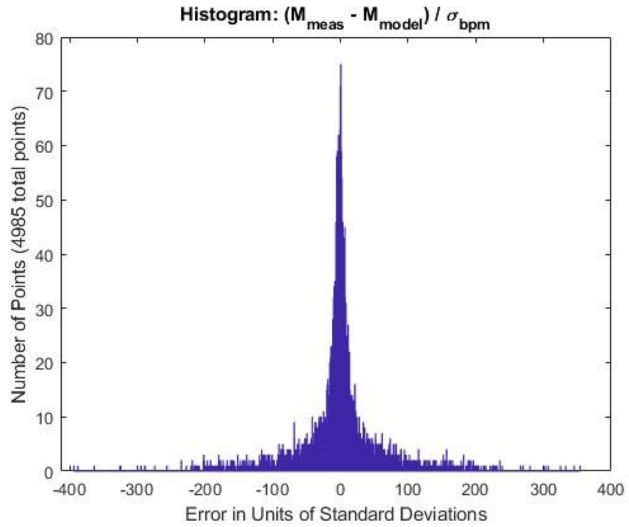
- Based on an old fashion time consuming MATLAB software taking in to account the ring lattice

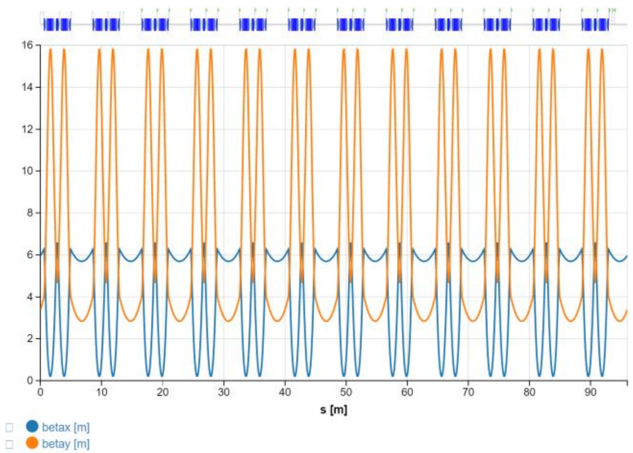
J.Biernat, R.Panaś in collaboration with G. Portman (co-author of the method) (Berkeley Lab, USA)

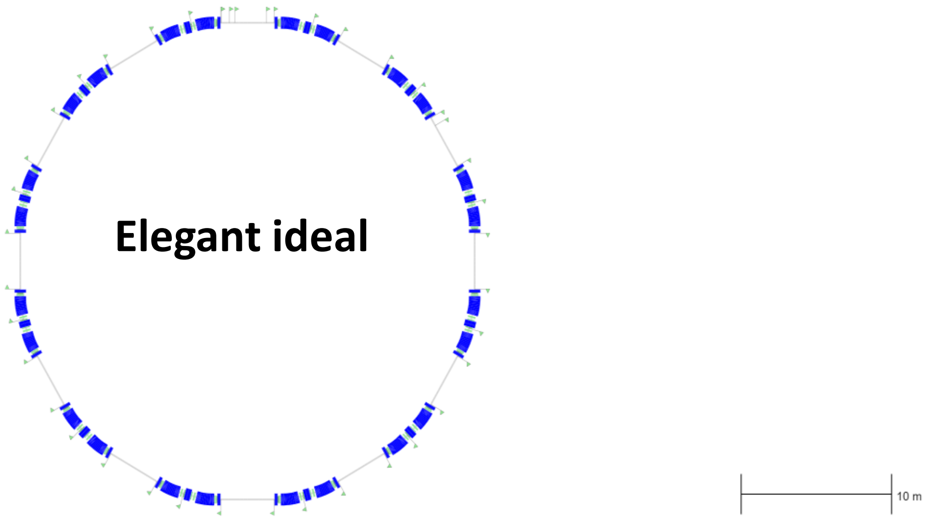
Beta functions











Current status of the beam orbit correction algorithm

corrector-to-BPM response matrix

$$\Delta\vec{x} = R\Delta\vec{\theta},$$

where: R - response matrix, $\Delta\vec{x}$ - vector of changing beam position in specific measurement points, $\Delta\vec{\theta}$ - vector of changing specific correctors strength.

beam position change according to angular kick change of corrector magnets.

SVD (singular value decomposition)

$$A = U(diag(w_i))V^T,$$

$$\vec{x} = \tilde{A}^{-1}b + \vec{x_0}$$

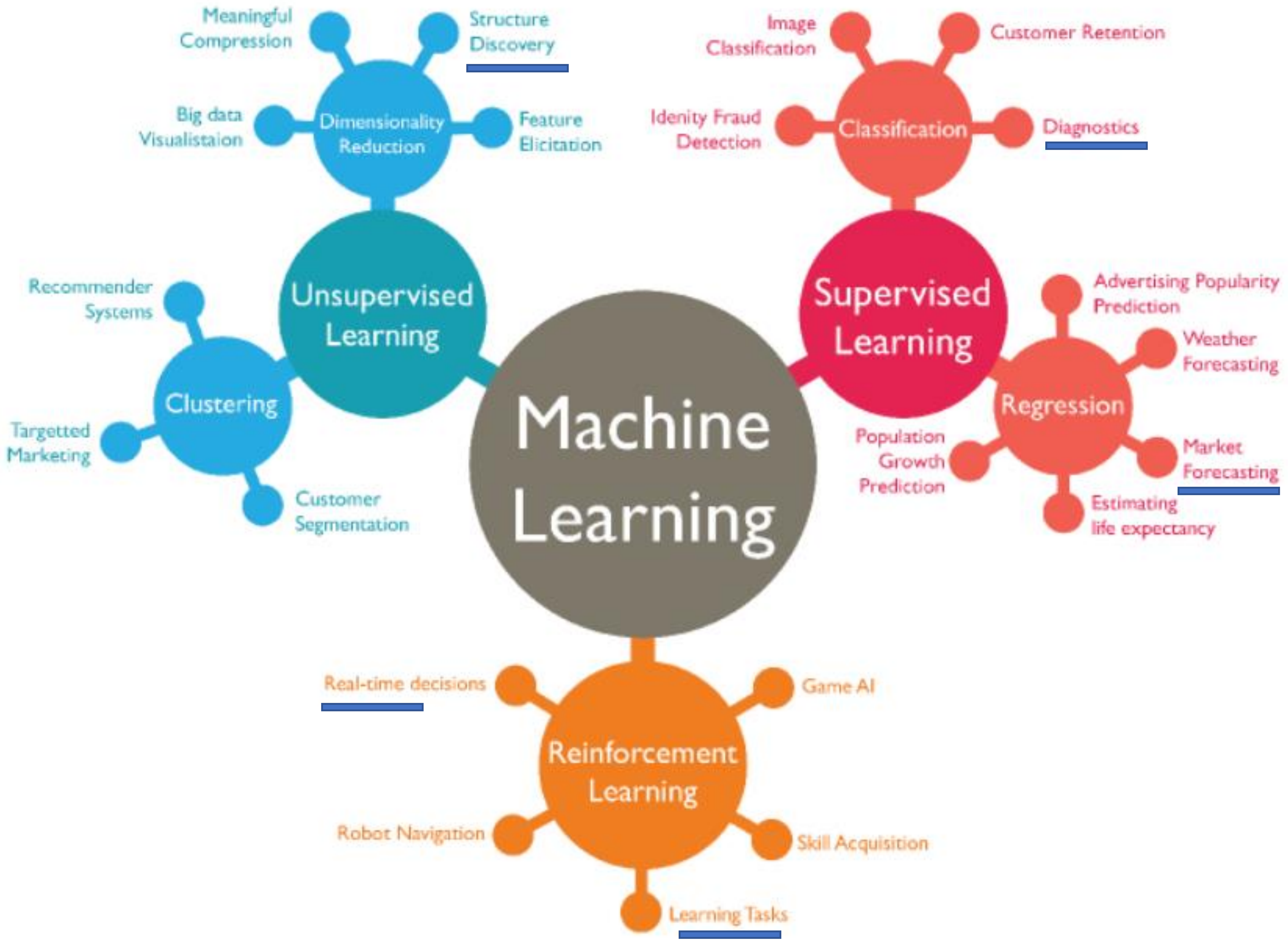
where:

$$\tilde{A}^{-1} = V\left(diag(\tilde{w}_i^{-1})\right)U^T,$$

$$\vec{x_0} \in Ker(A),$$

$$\tilde{w}_i^{-1} = \begin{cases} w_i^{-1} & \text{gdy } w_i \neq 0, \\ 0 & \text{gdy } w_i = 0 \end{cases}$$

https://synchrotron.uj.edu.pl/documents/1457771/136665849/P.Saga%C5%82o.PDF/e93fa526-d594-4b92-9076-30f01d576550


Machine Learning
Unsupervised Learning
Dimensionality Reduction
Meaningful Compression
Structure Discovery
Big data Visualistaion
Feature Elicitation
Clustering
Recommender Systems
Targetted Marketing
Customer Segmentation
Supervised Learning
Classification
Image Classification
Customer Retention
Idenity Fraud Detection
Diagnostics
Regression
Advertising Popularity Prediction
Weather Forecasting
Population Growth Prediction
Market Forecasting
Estimating life expectancy
Reinforcement Learning
Real-time decisions
Game AI
Robot Navigation
Skill Acquisition
Learning Tasks

Forecasting with ARIMA

ARIMA is an acronym for AutoRegressive Integrated Moving Average

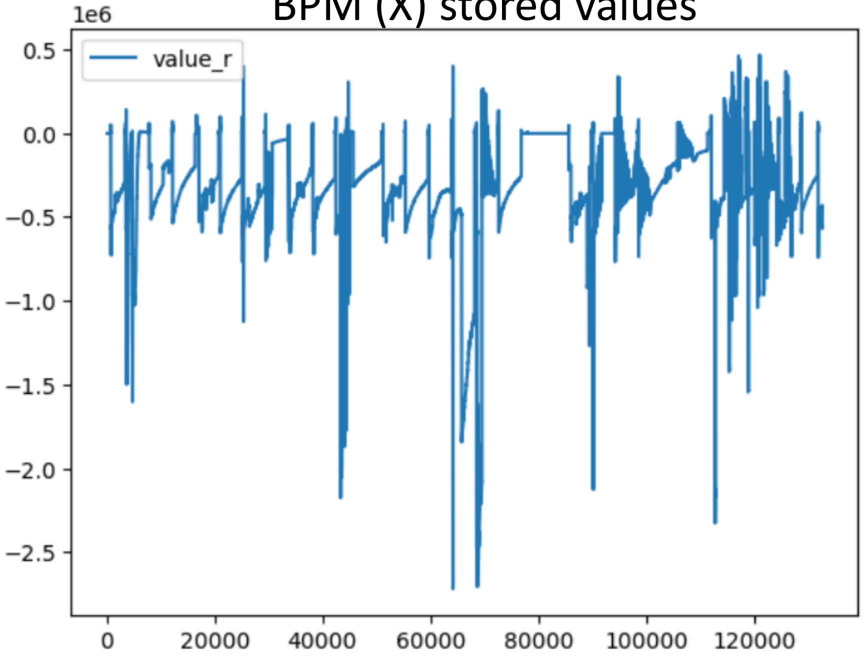
$$y'_t = c + \phi_1 y'_{t-1} + \cdots + \phi_p y'_{t-p} + \theta_1 \varepsilon_{t-1} + \cdots + \theta_q \varepsilon_{t-q} + \varepsilon_t,$$

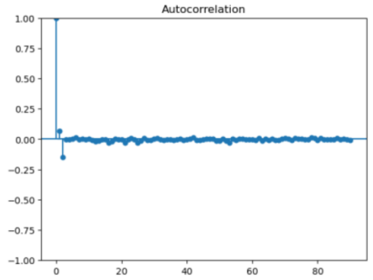
y'_t is the differenced series (it may have been differenced more than once).

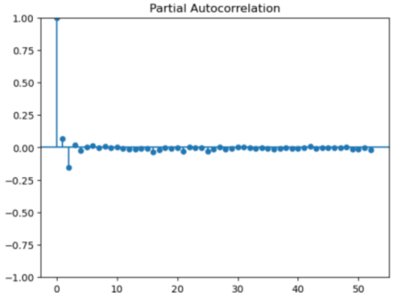
$p =$	order of the autoregressive part;
$d =$	degree of first differencing involved;
$q =$	order of the moving average part.

White noise	ARIMA(0,0,0)
Random walk	ARIMA(0,1,0) with no constant
Random walk with drift	ARIMA(0,1,0) with a constant
Autoregression	ARIMA(p,0,0)
Moving average	ARIMA(0,0,q)

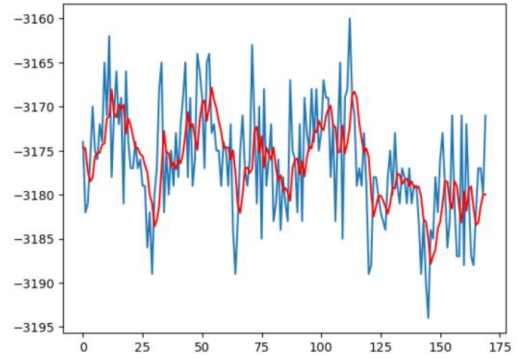
BPM (X) stored values







ARIMA(1,1,3)



Test done by, „BY HAND ” method, normally one iterates different sets of values (within a range)

https://otexts.com/fpp2/non-seasonal-arima.html

ARIMA is it good !?

- Taking into the account the „tuning method” it seems to do the job....

- Time consuming even for a 1000-point forecast (40 min on a Core i9), prefers single core computing
- Complex structure gives a very long a complex n-differential equation
- The tuning method can be automated, and this can be run on multi core CPU or GPU cluster
- **Single dimension input**, no possibility to preform correlation between different n-observables for the same experiment ☹
- Can not deal with seasonal events, can it detect predict a **singularity** event ? Doubtful....
- Still, it is the basics of market analysis and time series in general

Bayesian Structural Time Series

Is a technique used for feature selection, time series forecasting, nowcasting, inferring causal impact and other applications. The model is designed to work with time series data.

$$y_t = \tau_t + x_t'\beta + \delta_t + \epsilon_t, \epsilon_t \sim N(0, \sigma_y^2)$$

$$\tau_t = \tau_{t-1} + \alpha_t + \epsilon_t^\tau, \epsilon_t^\tau \sim N(0, \sigma_\tau^2)$$

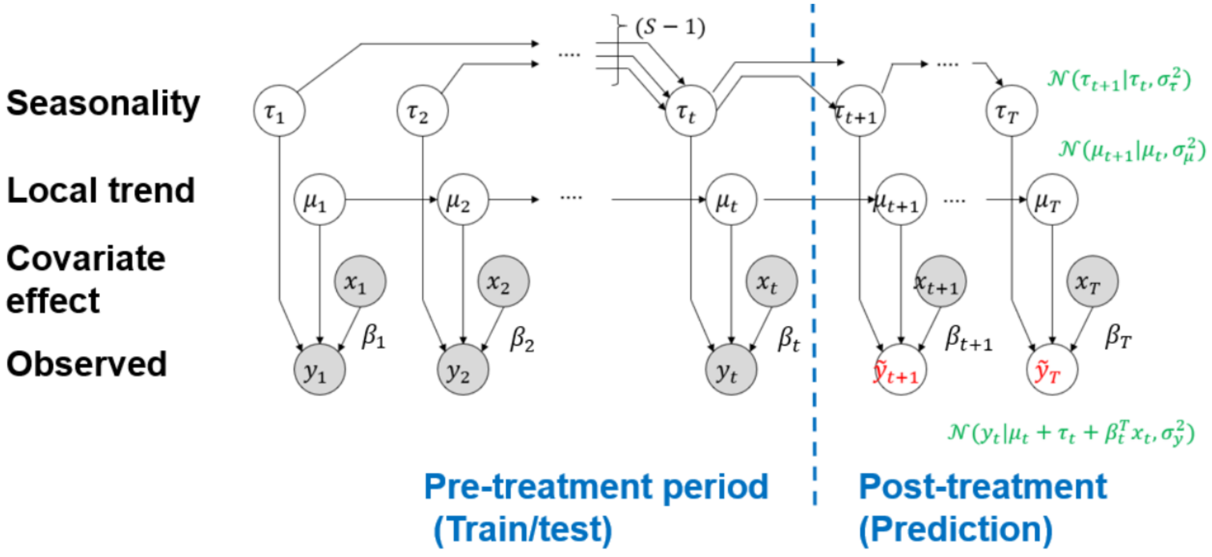
$$\alpha_t = \alpha_{t-1} + \epsilon_t^\alpha, \epsilon_t^\alpha \sim N(0, \sigma_\alpha^2)$$

$$\delta_t = -\sum_{s=1}^{S-1} \delta_{t-s} + \epsilon_t^\delta, \epsilon_t^\delta \sim N(0, \sigma_\delta^2).$$

arXiv:2011.00938v2 [econ.EM] 15 May 2022

Steps of the analysis

- **Kalman filter** The technique for time series decomposition.
- **Spike-and-slab** In this step, the most important regression predictors are selected.
- **Bayesian model averaging** Combining the results and prediction calculation.

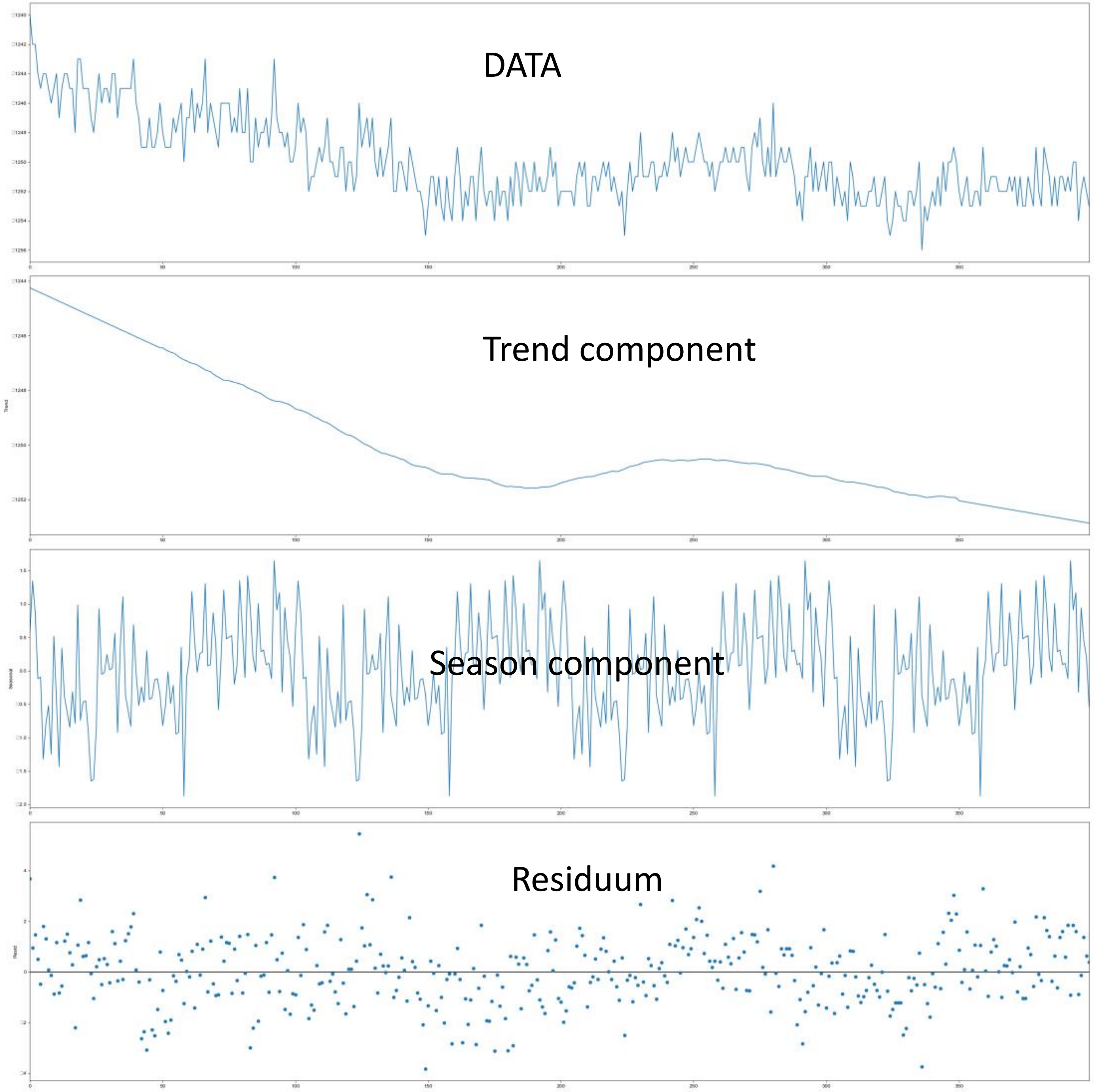


Bayesian Structural Time Series

- This is just a **benchmark test**
- Used low intensity beam BPM(X) red-out to

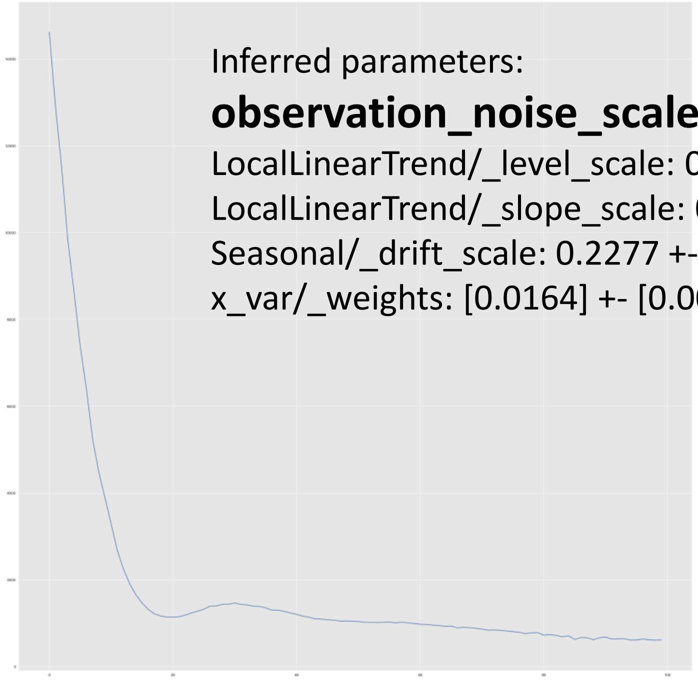
see the noise effect

- The method is sensitive to the trend in data and the weak season component
- This method is heavy in the sense of GPU utilization, this test took 5 min on a 5000 RTX Quadro, 3 GB of GPU ram was used for the whole procedure
- **Low sampling rate of 1000 was used**



Bayesian Structural Time Series

- The model for the sake of the test is **low precision** (1000) samples
- Five components used, scaling factor, local linear trend (level and slope scale), seasonal component and regression component
- Memory consumption is less then 1 Gb
- Training speed is 1-2 min



Inferred parameters:

observation_noise_scale: 1.005 +- 0.1704

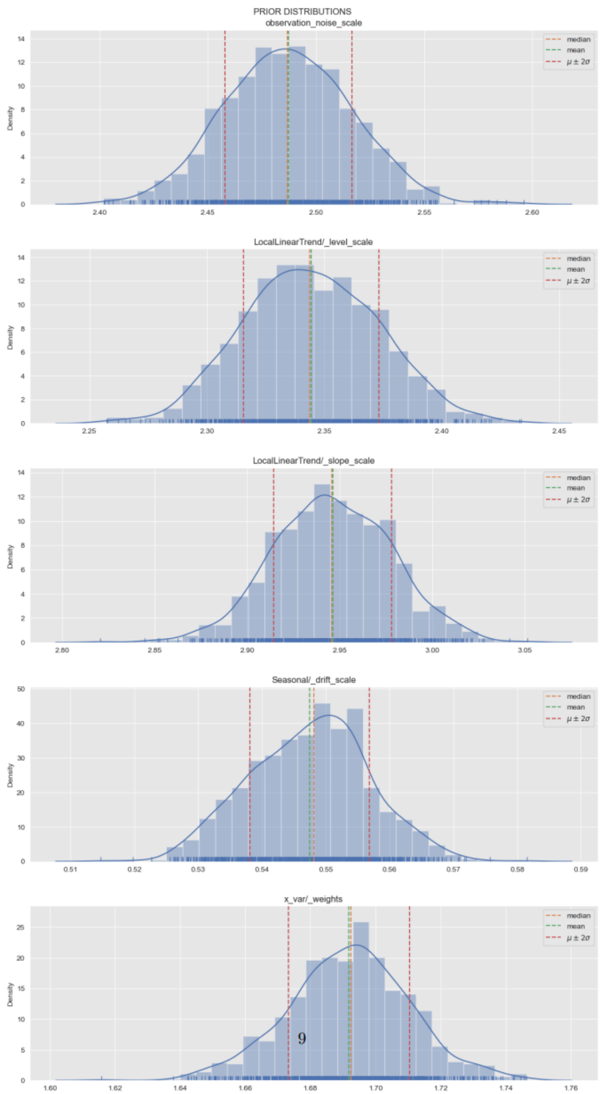
LocalLinearTrend/_level_scale: 0.5799 +- 0.1773

LocalLinearTrend/_slope_scale: 0.0755 +- 0.0190

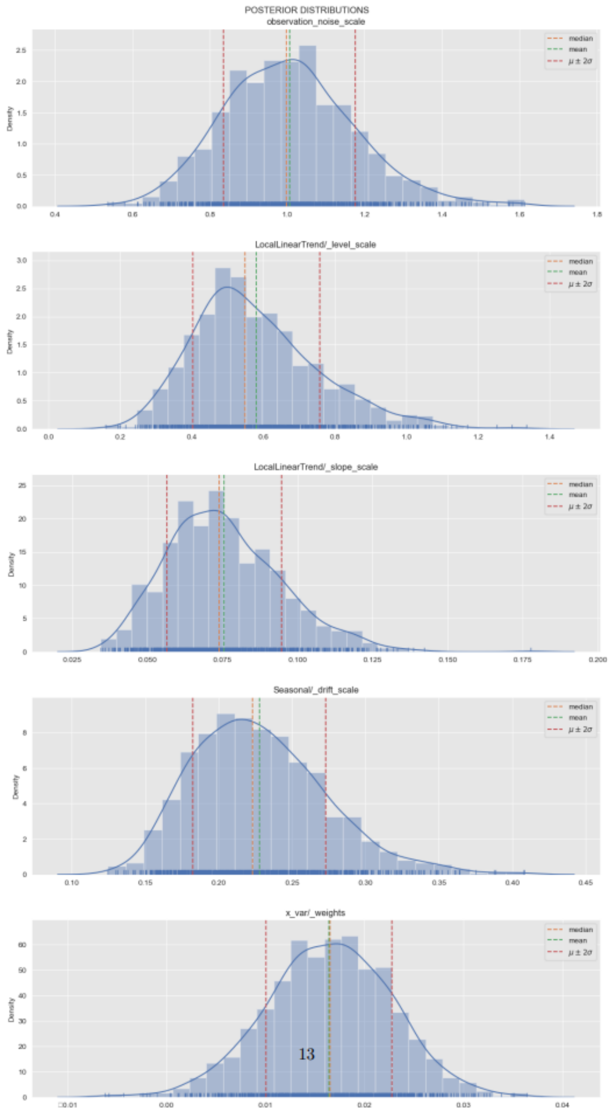
Seasonal/_drift_scale: 0.2277 +- 0.0452

x_var/_weights: [0.0164] +- [0.006]

Prior distributions

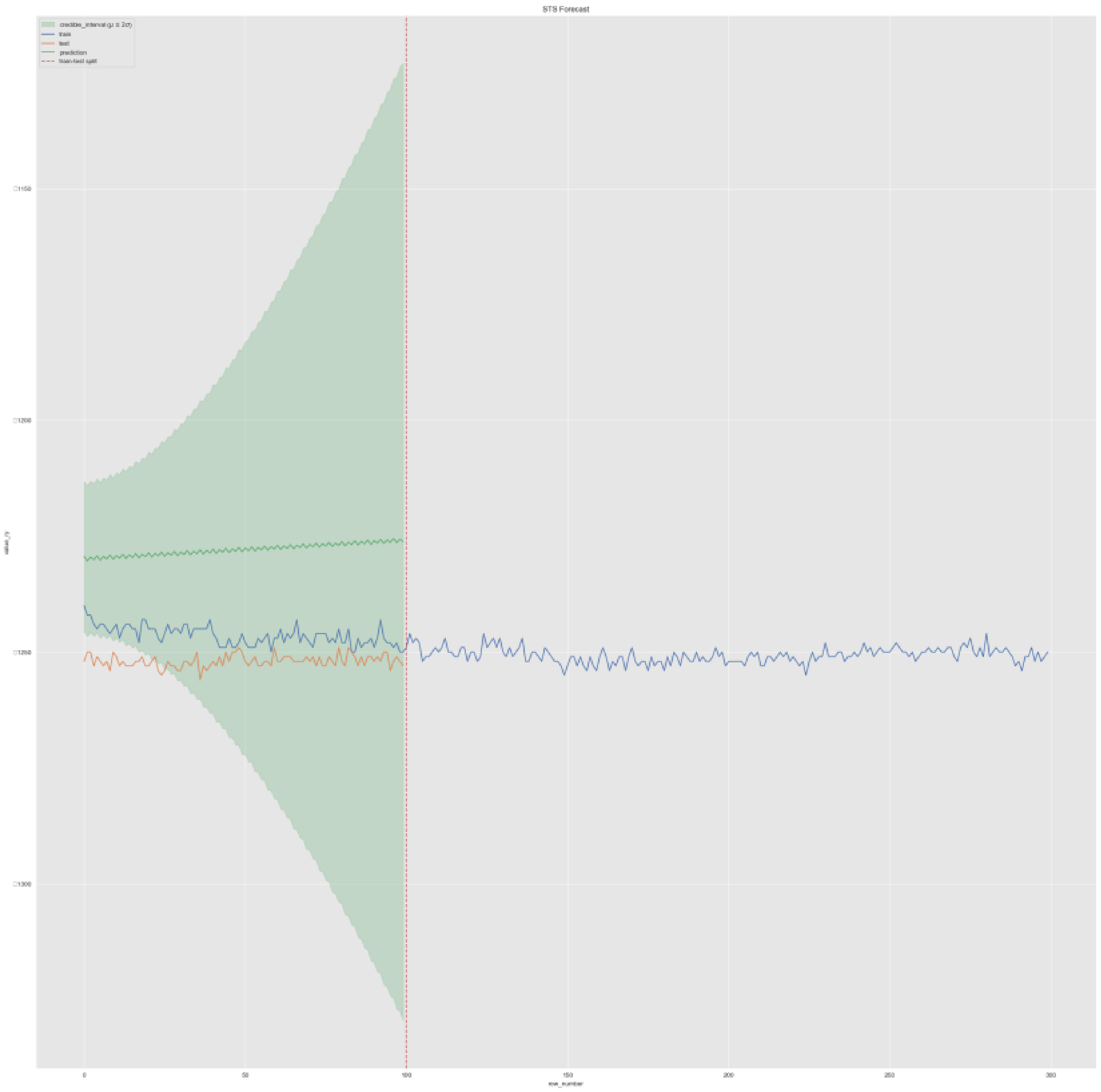


Posterior distributions



Bayesian Structural Time Series

- We have the prediction ☺
- As expected, it is far form being precise
- We generated essentially white noise, with some trend, this is expected
- **More tests needed on a more powerful setup, cloud computing** (jupyter notebook with multi-GPU support, training/testing GPU and forecasting GPU)
- On average per one forecast point we have 5 distributions with thousand samples, a killer for this method for the time being

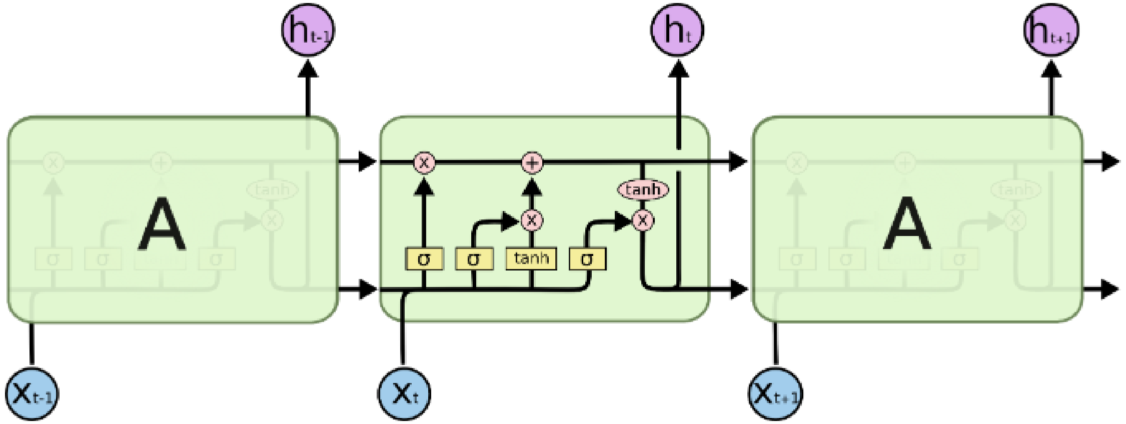


Long Short-Term Memory networks

Long Short-Term Memory networks – usually just called "LSTMs" – are a special kind of RNN, capable of learning long-term dependencies.

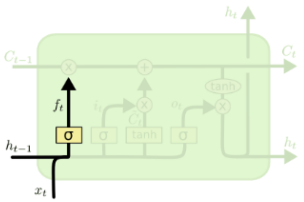
Key features:

- ✓ learning memory
- ✓ Non- sequential
- ✓ Fast, utilize many cores on a GPU
- ✓ Low memory consumption compared to BSTS
- ✓ n- dimensional input



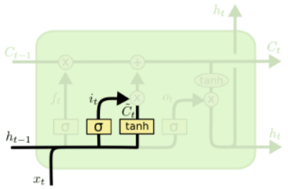
The repeating module in an LSTM contains four interacting layers.

Do we forget ?



$$f_t = \sigma\left(W_f \cdot [h_{t-1}, x_t] \; + \; b_f\right)$$

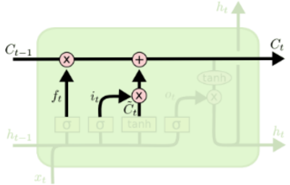
Do we update ?



$$i_t = \sigma\left(W_i \cdot [h_{t-1}, x_t] \; + \; b_i\right)$$

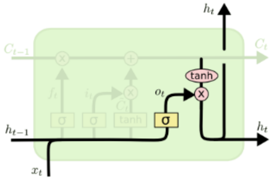
$$\tilde{C}_t = \tanh(W_C \cdot [h_{t-1}, x_t] \; + \; b_C)$$

We shift the cell to a new state☺



$$C_t = f_t * C_{t-1} + i_t * \tilde{C}_t$$

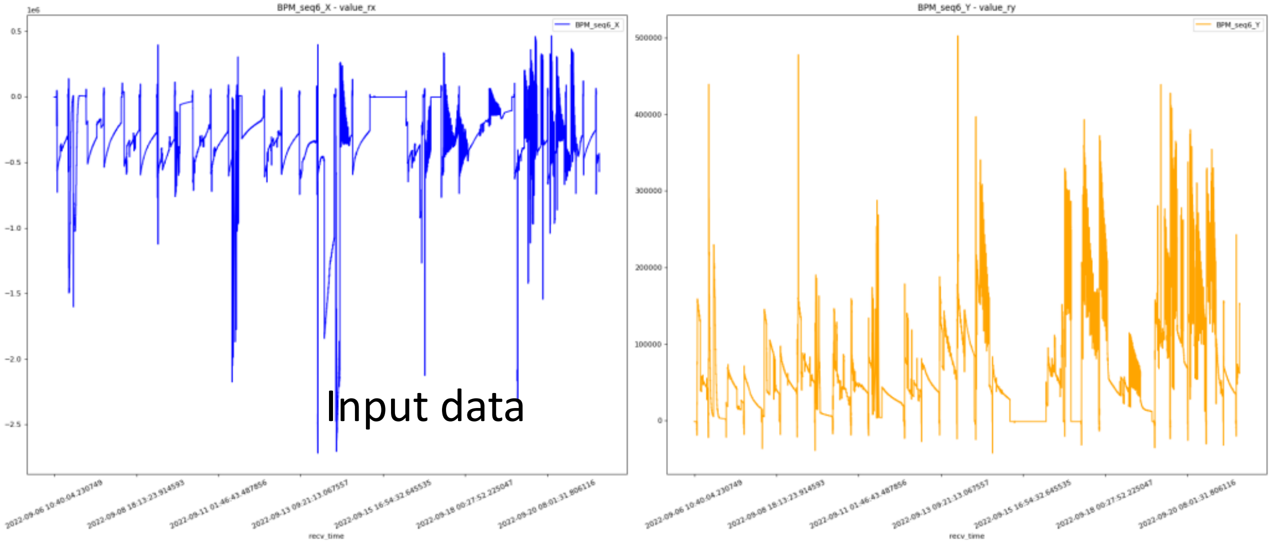
We get the output☺



$$o_t = \sigma\left(W_o \; [h_{t-1}, x_t] \; + \; b_o\right)$$

$$h_t = o_t * \tanh\left(C_t\right)$$

Long Short-Term Memory networks

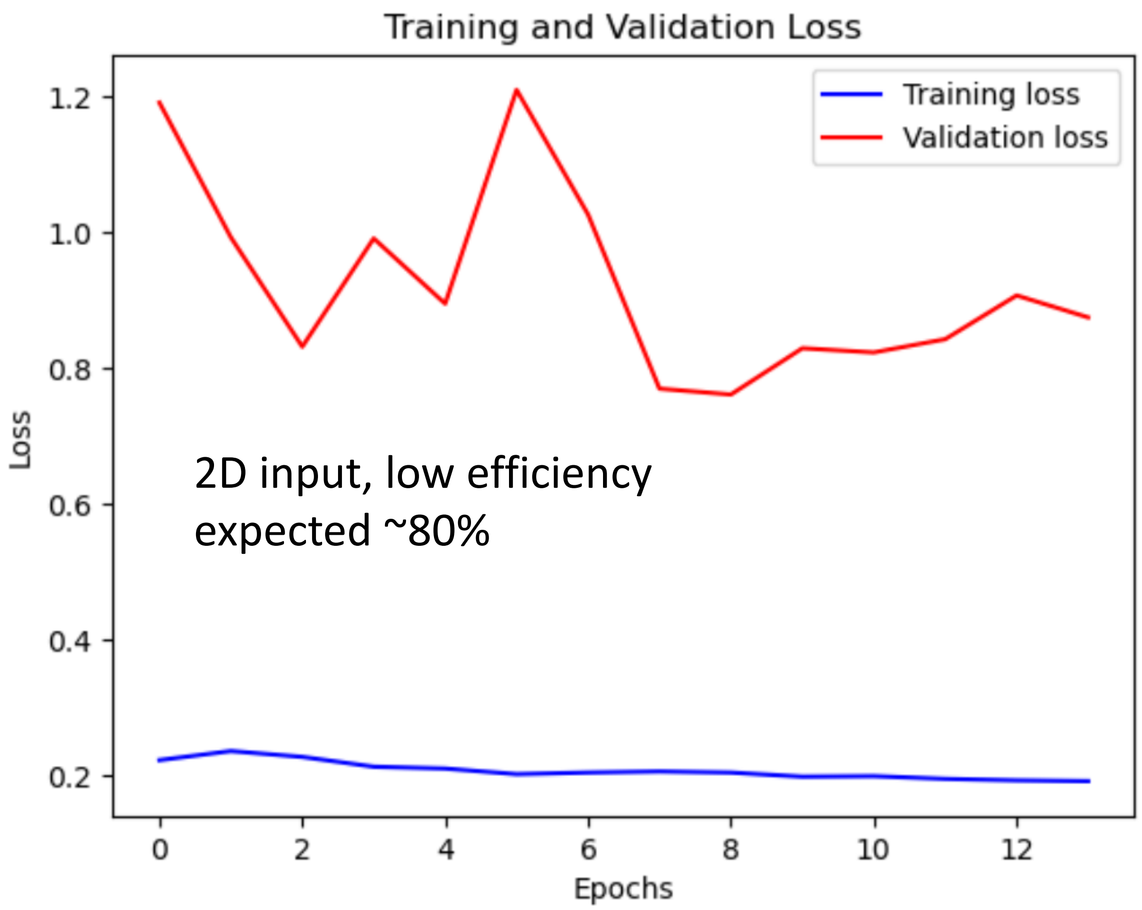



```
Model: "model"
_________________________________________________________________
 Layer (type)                Output Shape              Param #
=================================================================
 input_1 (InputLayer)        [(None, 1500, 2)]         0

 lstm (LSTM)                 (None, 32)                4480

 dense (Dense)               (None, 1)                 33

=================================================================
Total params: 4,513
Trainable params: 4,513
Non-trainable params: 0
_________________________________________________________________
```

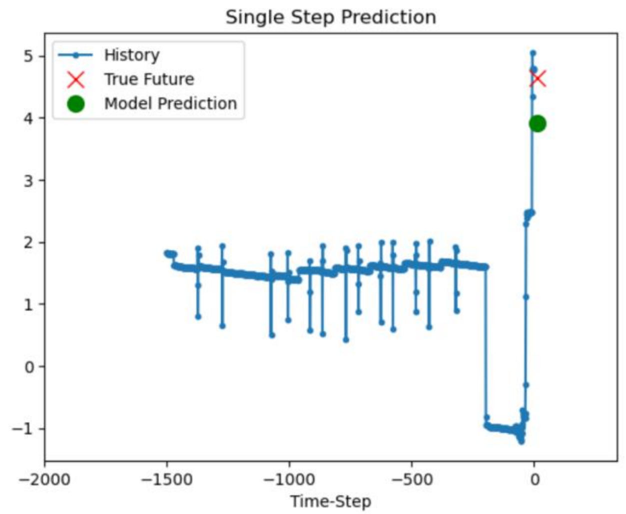
```
Epoch 1/20
3733/3734 [============================>.] - ETA: 0s - loss: 0.2220
Epoch 1: val_loss improved from inf to 1.19001, saving model to
model_checkpoint.h5
3734/3734 [==============================] - 143s 38ms/step - loss: 0.2231 -
val_loss: 1.1900
Epoch 2/20
3733/3734 [============================>.] - ETA: 0s - loss: 0.2358
Epoch 2: val_loss improved from 1.19001 to 0.99194, saving model to
model_checkpoint.h5
3734/3734 [==============================] - 141s 38ms/step - loss: 0.2364 -
val_loss: 0.9919
Epoch 3/20
3733/3734 [============================>.] - ETA: 0s - loss: 0.2270
Epoch 3: val_loss improved from 0.99194 to 0.83112, saving model to
model_checkpoint.h5
3734/3734 [==============================] - 143s 38ms/step - loss: 0.2278 -
val_loss: 0.8311
Epoch 4/20
3733/3734 [============================>.] - ETA: 0s - loss: 0.2118
Epoch 4: val_loss did not improve from 0.83112
3734/3734 [==============================] - 143s 38ms/step - loss: 0.2134 -
val_loss: 0.9903
Epoch 5/20
```

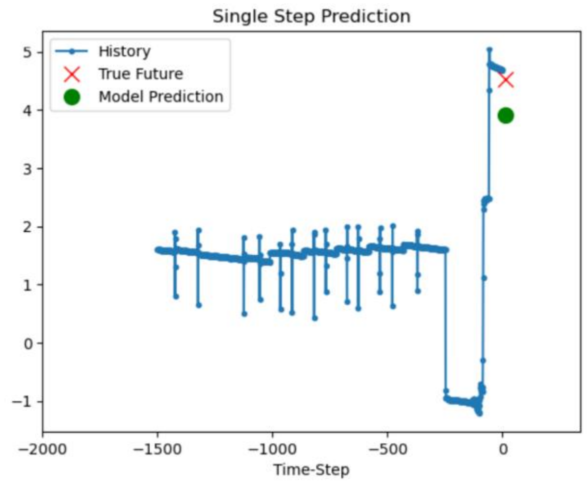
Checkpoint training method, kills training when the loss does not improve over time

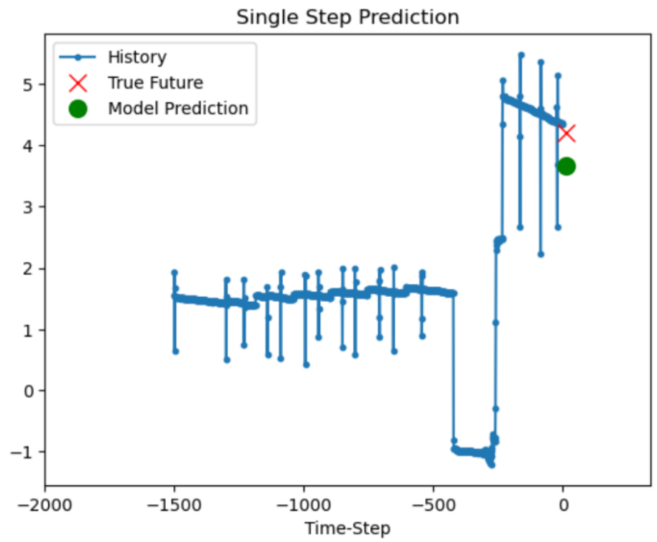
Long Short-Term Memory networks

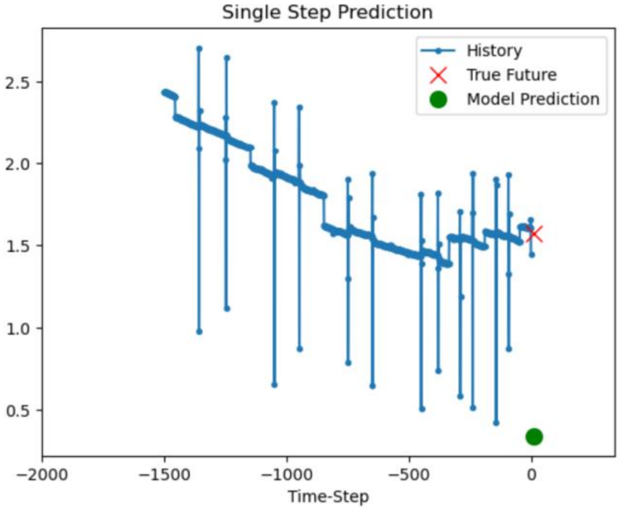


2D input, low efficiency
expected ~80%









20 ms for one point forecast!

Conclusions

- A lot has been done in the sense of militance and operation, the ring runs at the desired beam intensity
- We are moving into modern python **diagnostics tools**
- The **SOLARIS** facility has the possibility of addressing a lot of important topics form the point of hardware, software and scientific point. Ranging form solid state to nuclear physics.
- Using ML/neural network/ forecasting tools will be challenging for our multi-input dataset but if successful may benefit us with a powerful **diagnostic tool** and enhance the **beam correction**
- We can provide a valuable contribution into the synchrotron radiation society (~50+ operating facilities in the world)