DEELS 21- Diagnostics Experts of European Light Sources 2021

7 July 2021
Virtual- Webex Platform
Europe/Zurich timezone

Computer vision application for real-time beam tracking in pinhole image systems at ALBA

(Work in progress)

Andriy Nosych (ALBA-CELLS, Spain)

Rockets are machines, but so far they went to space not because of Machine Learning.
Rockets go to space thanks to precise models.

Precise models beat good statistics!

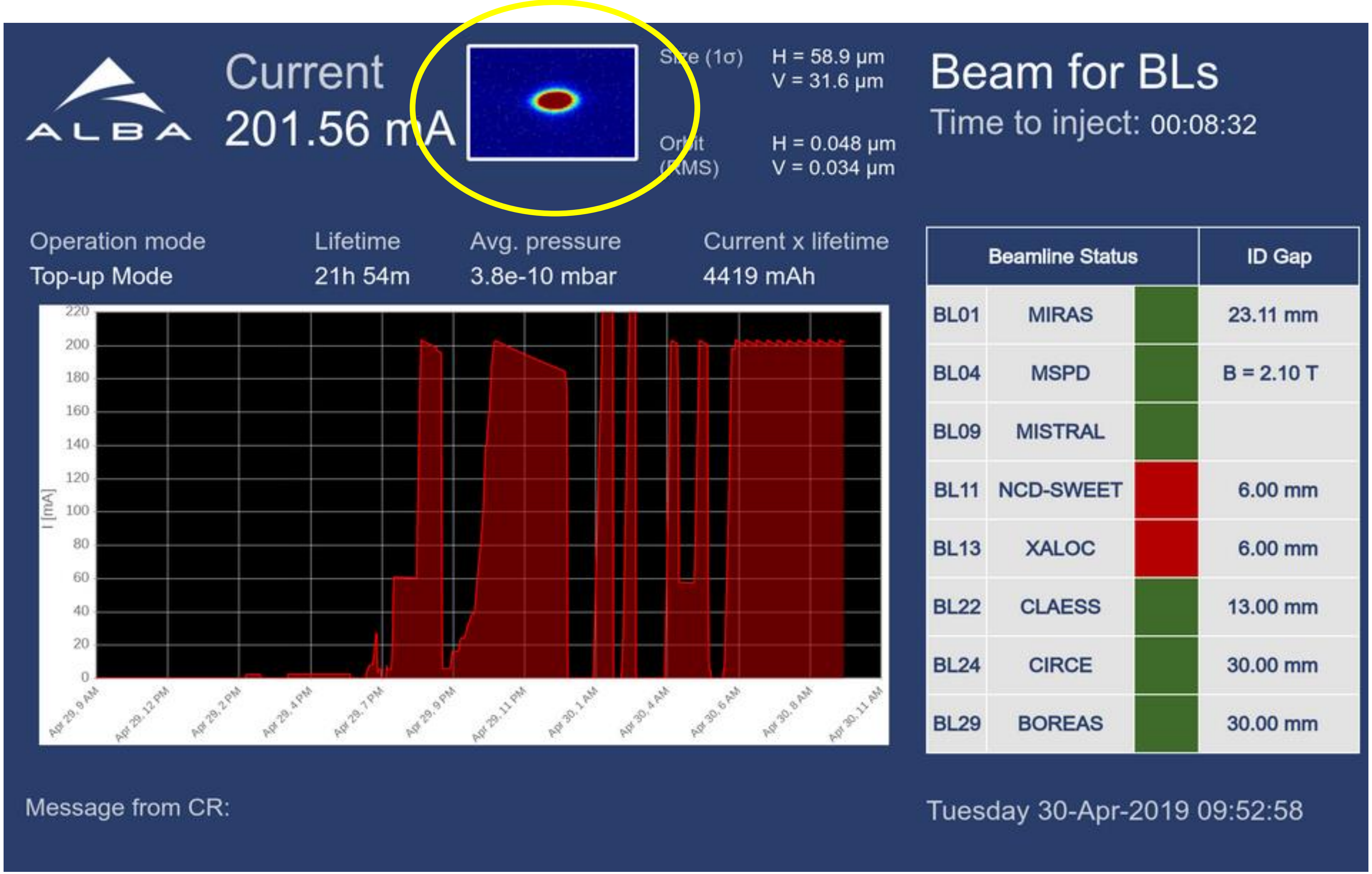
Particle accelerators are also precise machines.
ML is not very common here yet, more auxiliary.

Common ML applications in accelerators:

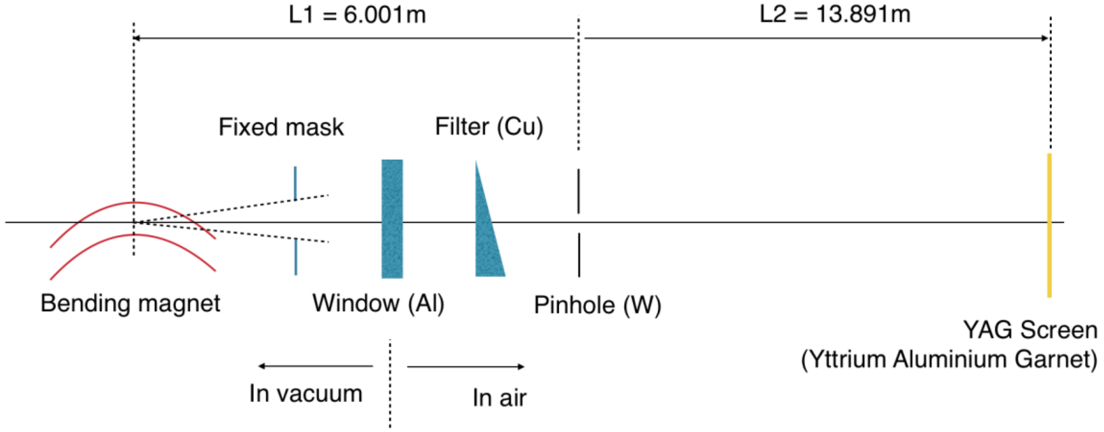
- Design + performance optimization
- Anomaly detection
- Fault prediction
- Models from data

What about accelerator diagnostics and beam dynamics?
Not easy to find an application!

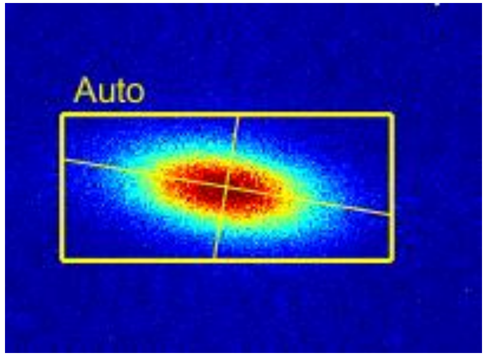
ALBA machine status screen



Pinhole system: how its done



X-ray pinhole camera provides transverse size measurements of the electron beam:

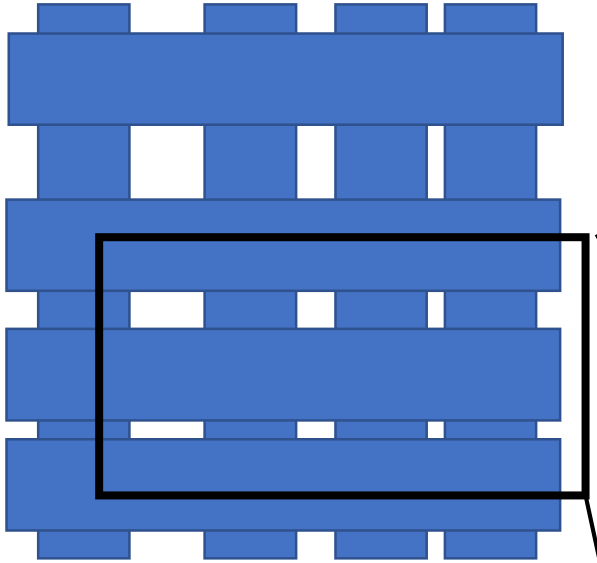


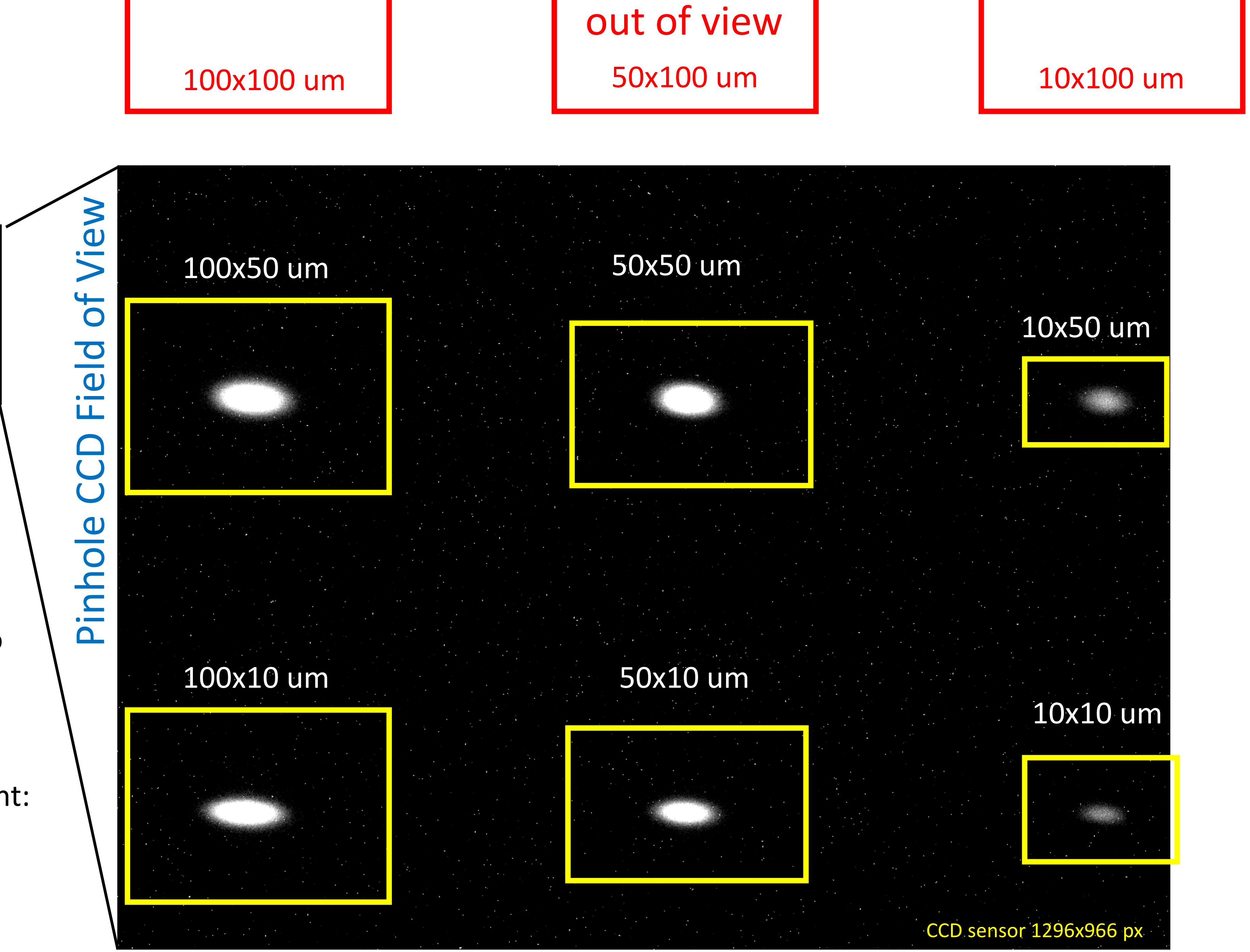
$$\sigma_{YAG}=(L_2/L_1)\ \sigma_{source}$$

$$\sigma^2_{\mathrm{YAG}} = (X\sigma_{\mathrm{b}})^2 + (\sigma_{\mathrm{PSF}})^2$$

$$\sigma_{\mathrm{PSF}} = \sqrt{\sigma^2_{\mathrm{blur}} + \sigma^2_{\mathrm{DIFF}} + \sigma^2_{\mathrm{screen}}}$$ ← blurring, diffraction, screen resolution

$$\sigma_{\mathrm{diff}} = \frac{\sqrt{12}}{4\pi}\frac{\lambda L_2}{w} \qquad \sigma_{\mathrm{blur}} = \frac{w(L_1+L_2)}{\sqrt{12}L_1}$$





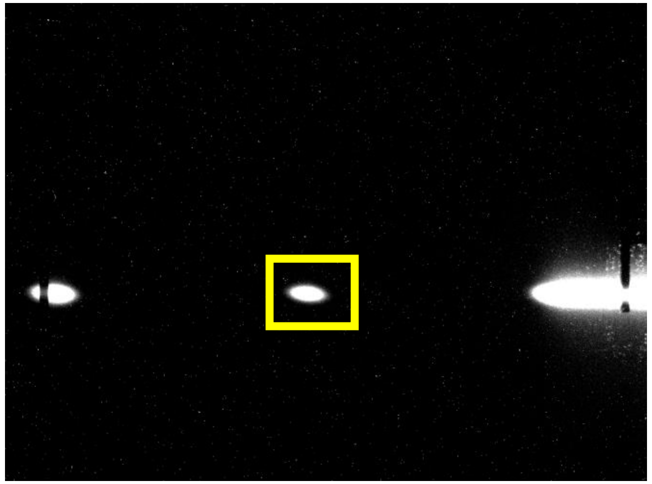
At Alba there are actually 2 pinhole systems, both able to see up to 6 beam images at a time

Each beam image has different:

- source pinhole H&V size
- point spread function
- ROI centered around it

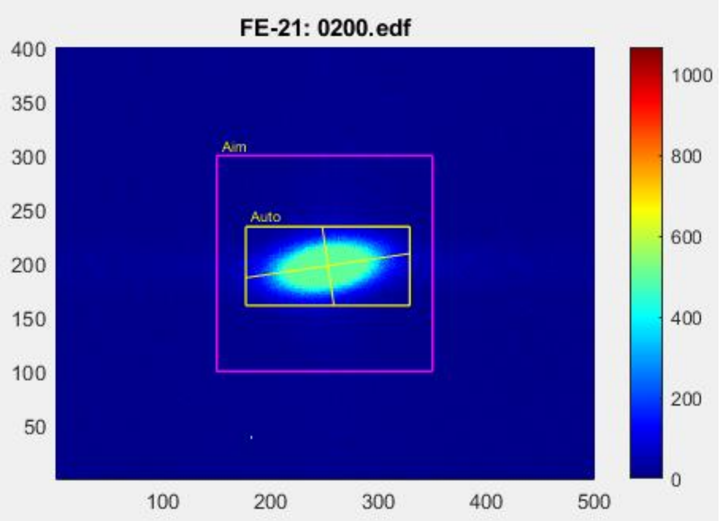
Beam spot parameters are manually fixed for fitting

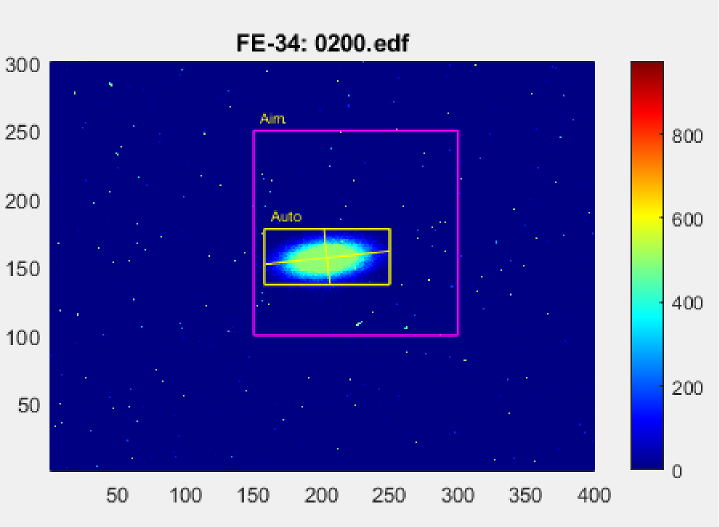
We have to tell the system where to look (ROI), and hope the conditions won't change (e.g. beam moves out or pinhole motors are moved for experiments)



3Hz refresh rate to control system

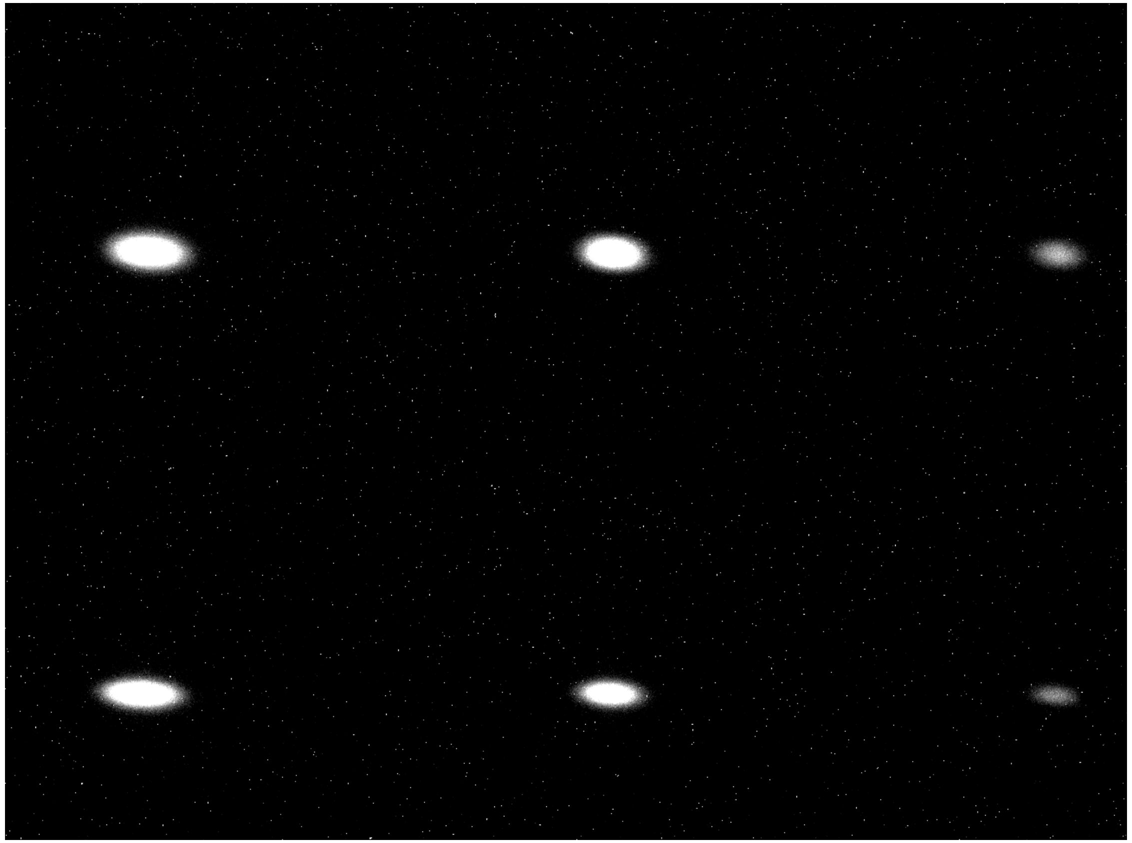
Math analysis within ROIs of both pinholes





==== FE-21 ====	==== FE-34 ====
filename: 0086.edf	filename: 0086.edf
Amp = 1074.42	Amp = 970.28
Bkg = 22.0649	Bkg = 0.0000
X_0 = 254.14 [px]	X_0 = 203.57 [px]
Y_0 = 198.29 [px]	Y_0 = 156.72 [px]
X_0 = 466.38 [um]	X_0 = 594.48 [um]
Y_0 = 323.34 [um]	Y_0 = 460.78 [um]
σ_X (2D) = 56.23 [um]	σ_X (2D) = 55.21 [um]
σ_Y (2D) = 22.33 [um]	σ_Y (2D) = 23.10 [um]
σ_X (2D) = 30.72 [px]	σ_X (2D) = 19.04 [px]
σ_Y (2D) = 13.92 [px]	σ_Y (2D) = 8.16 [px]
σ_X (1D) = 55.61 [um]	σ_X (1D) = 52.98 [um]
σ_Y (1D) = 23.61 [um]	σ_Y (1D) = 23.03 [um]
tilt = 0.147 [rad]	tilt = 0.109 [rad]
tilt = 8.4 [deg]	tilt = 6.2 [deg]
ϵ_H = 5.2985	ϵ_H = 3.6421
ϵ_V = 0.0219	ϵ_V = 0.0197
K = 0.41 [%]	K = 0.54 [%]
Int_{px} = 25.38	Int_{px} = 9.17
Err_H 1D = 197.85	Err_H 1D = 595.05
Err_V 1D = 1182.07	Err_V 1D = 568.26
Err 2D = 4.51e+06	Err 2D = 6.08e+06

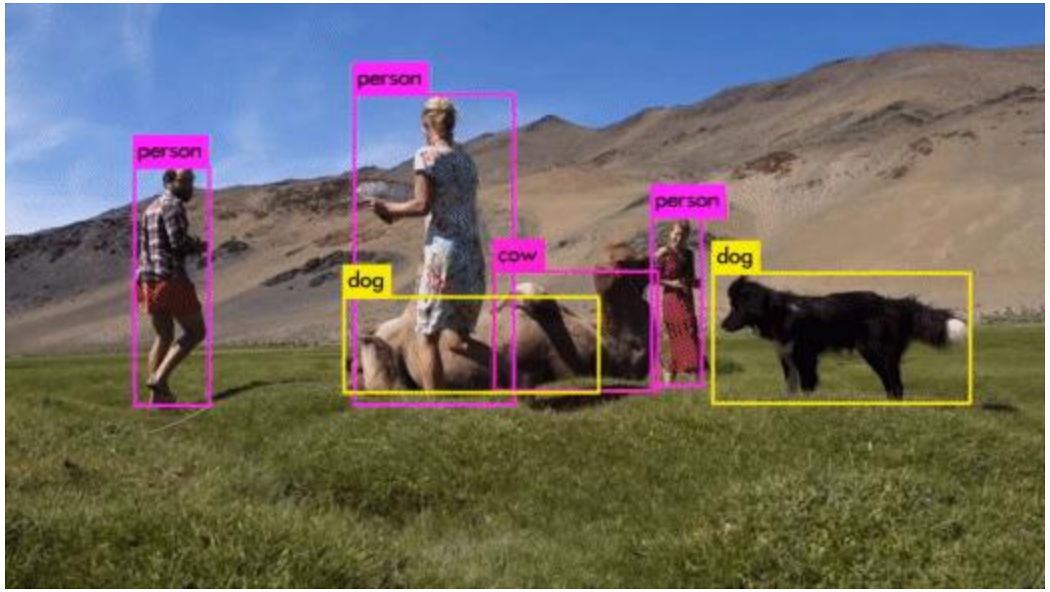
What if a machine would look at this image, and recognize what is what?



Machine Learning: how its done

Structure: Computer vision

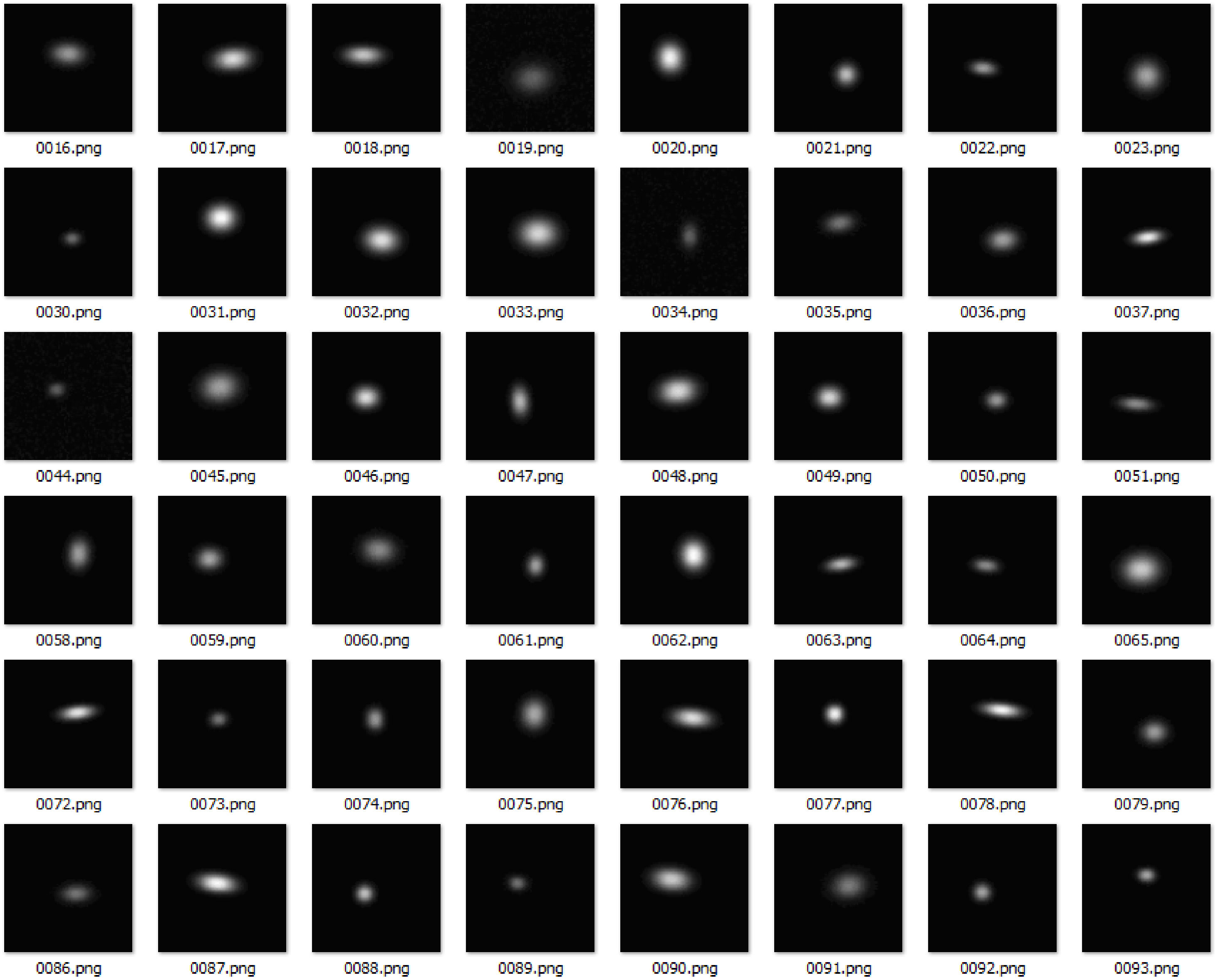
- Learning: **Supervised**
  - Task: **Classification**
    - Architecture: **ImageAI with Tensorflow2.4 backend** [https://imageai.readthedocs.io]
      - Algorithm: **YOLOv3** [https://pjreddie.com/darknet/yolo/]



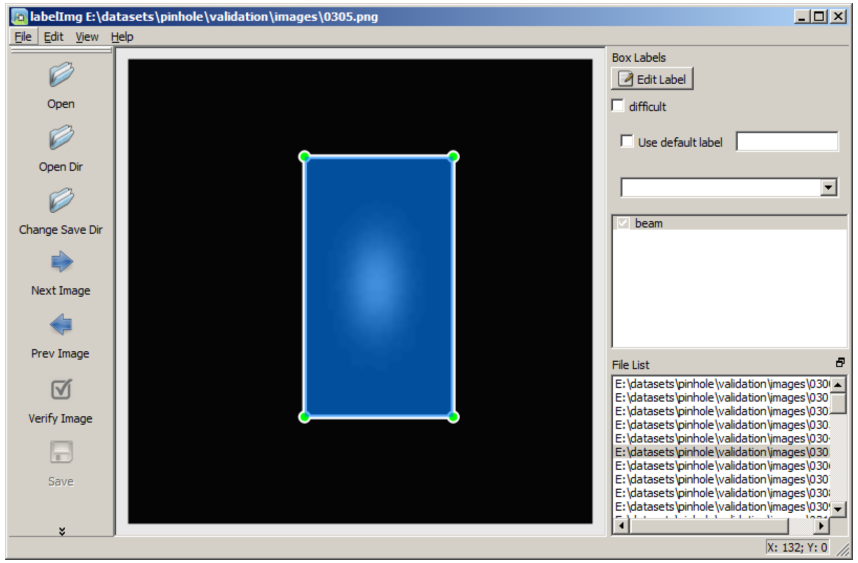
YOLO: You Only Look Once

A real-time object detection system, based on convolutional NN which looks at the whole image and predicts bounding boxes with classifiers

Model trained on randomly generated Gaussians with annotations

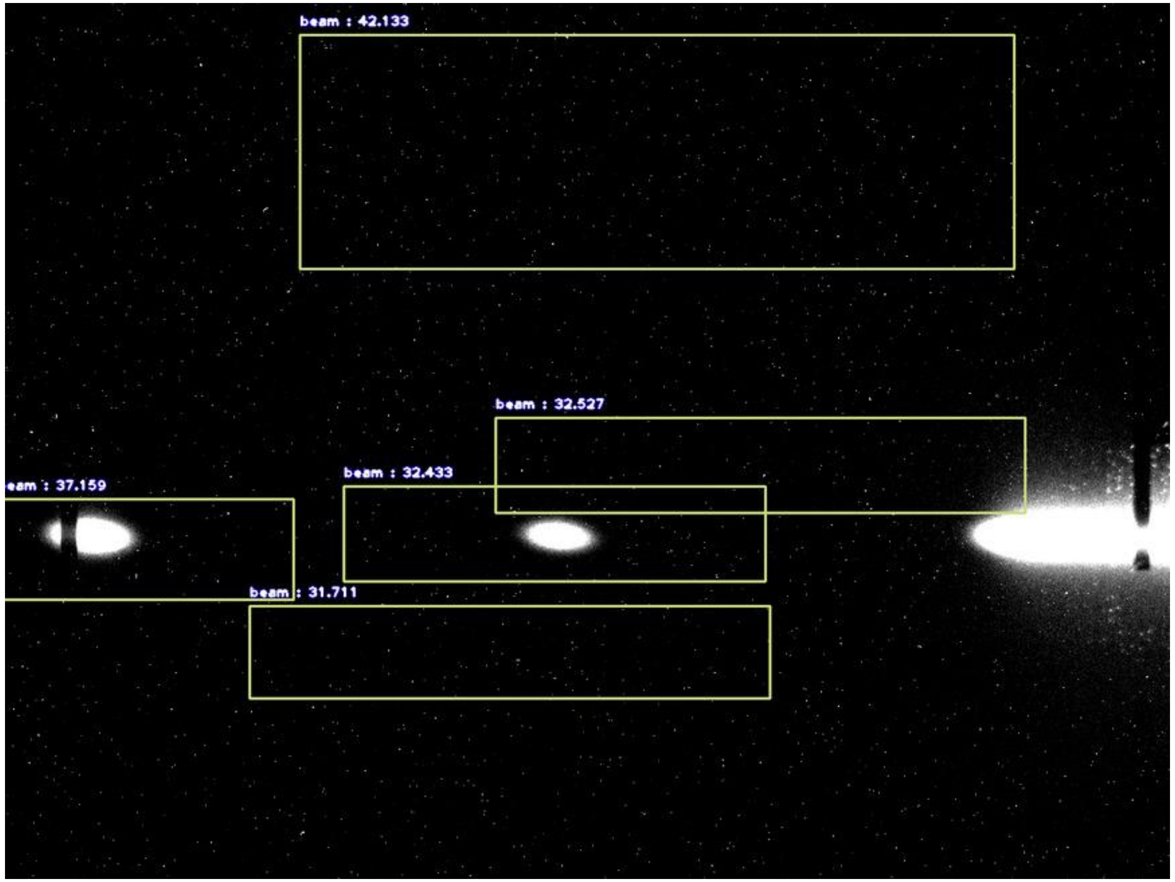


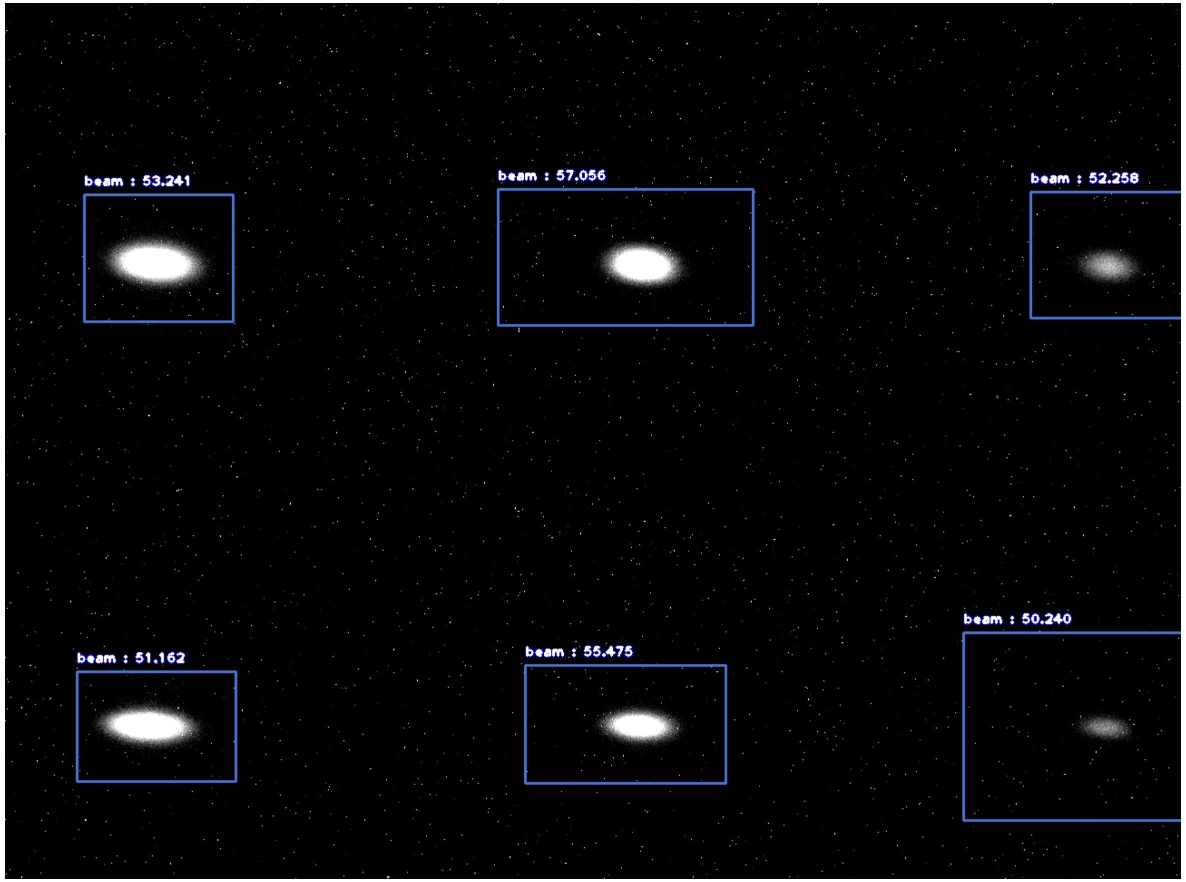
Annotations automatically generated and verified with labelImg.py



Learning goes wrong

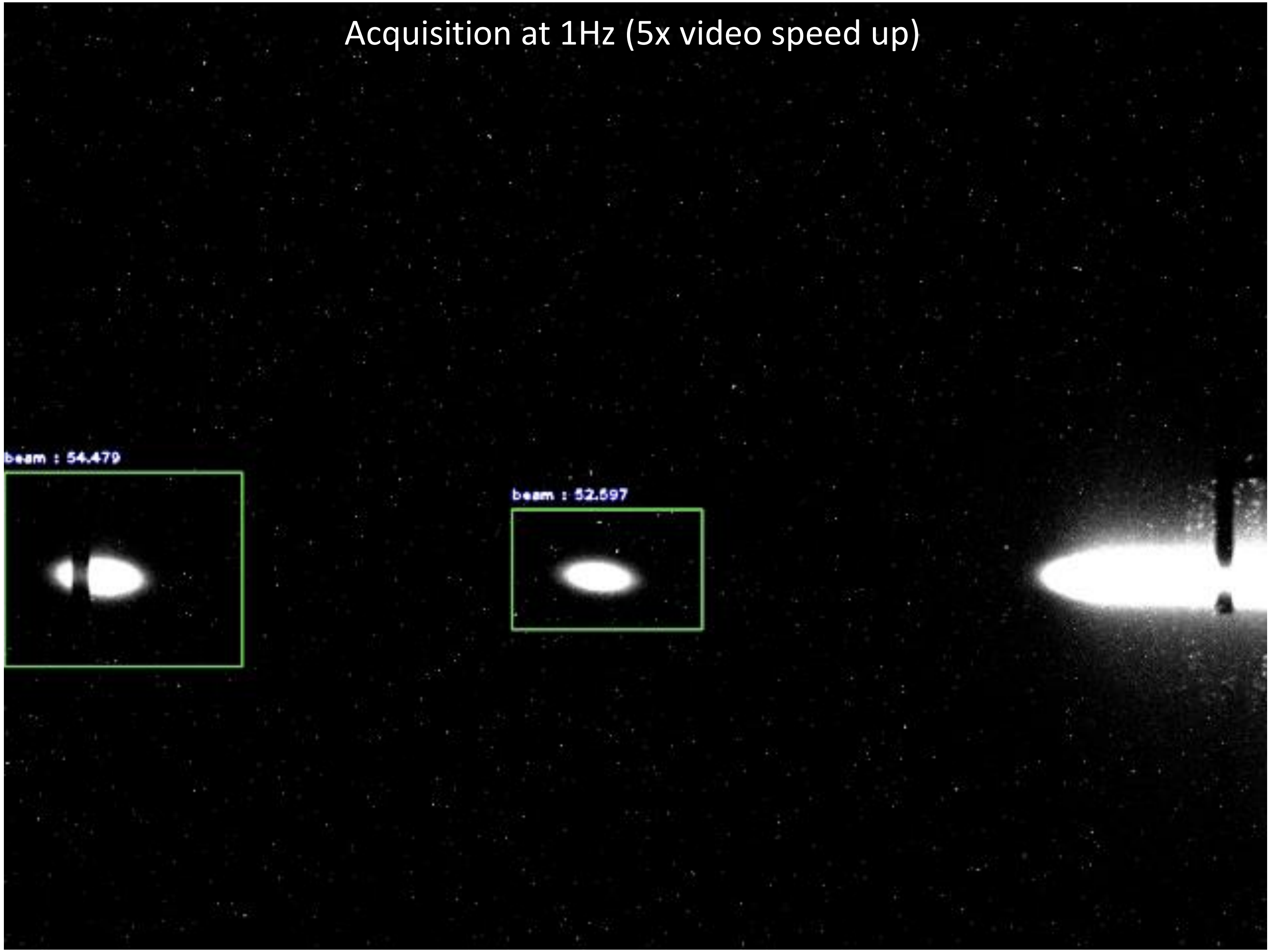
Learning goes right





8 epochs
1000 training images 72x72 px
Time of each epoch: 6h (3GHz CPU)
Not enough training epochs?
Insufficient/wrong learning data?

23 epochs
300 training images 100x100 px
Time of each epoch: 2h (3GHz CPU)
Model size: 250 Mb



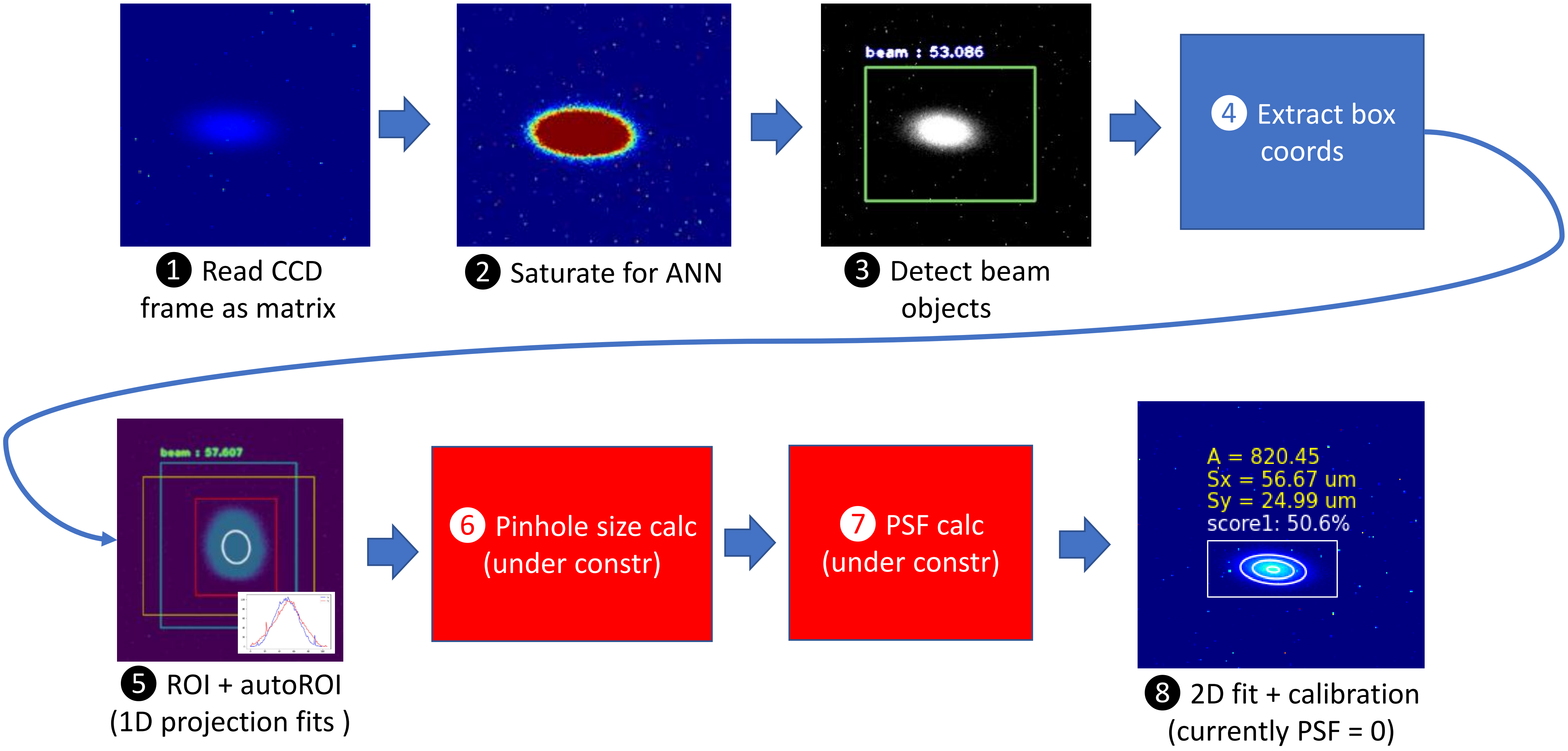
Current AAN performance:

<2 FPS detection speed on a laptop
250 Mb model size
Trained on a single object (“beam”)

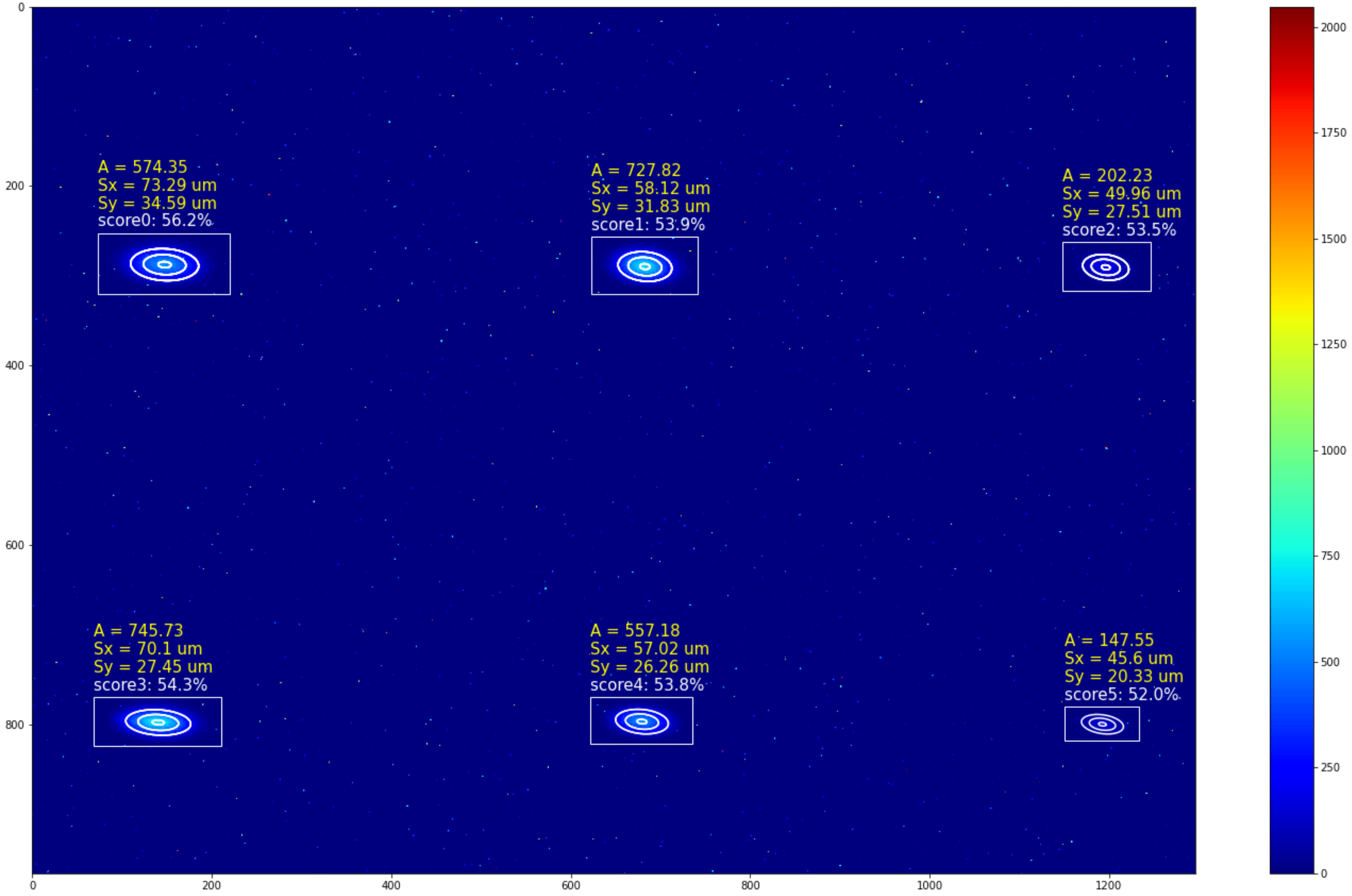
Questions to ANN

- How many Epochs do you really need?
- How to further optimize the confidence score?
- ROI sometimes off, why?
- Can you detect faster?
- Can you have a smaller model size?

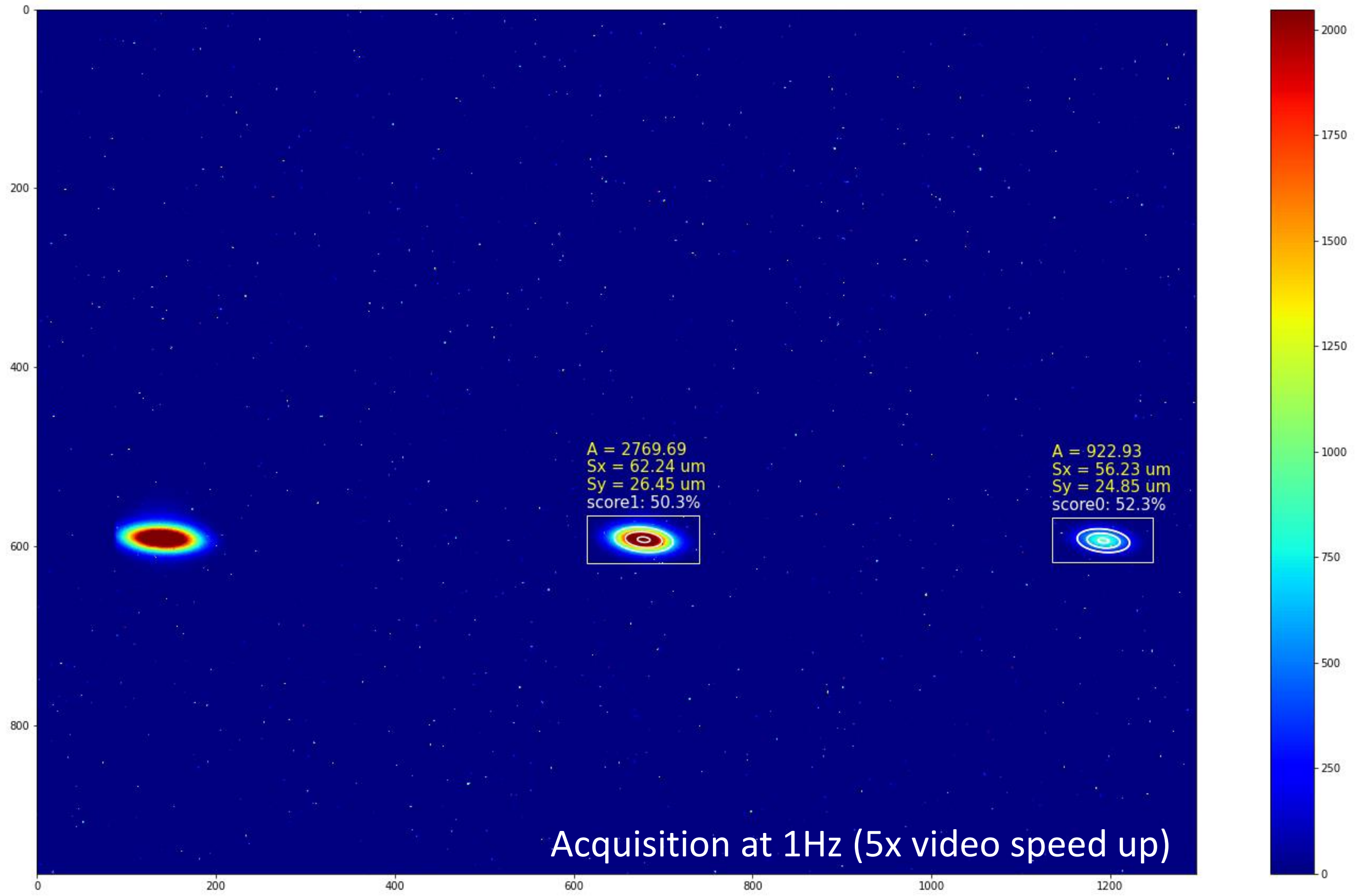
Numerical analysis: how its done



Numerical analysis:

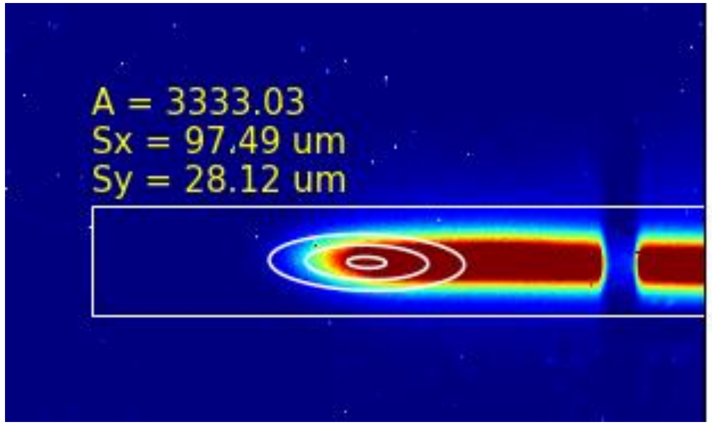


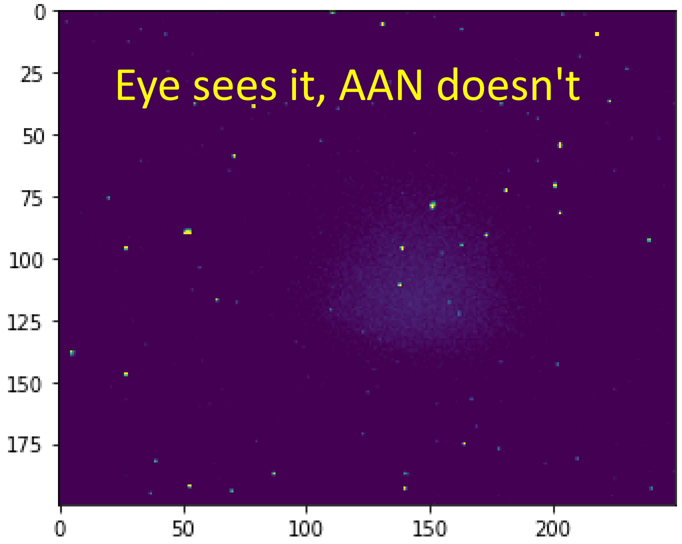
Numerical analysis:



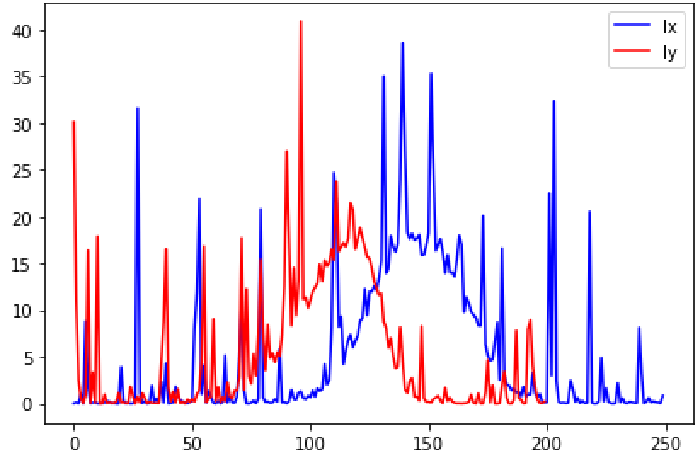
Challenges:

Ignore beam fan





ANN sees it, math doesn’t



<u>Also</u>

improve detection score (now 45-55%)

frame analysis speed (now 0.5-2 fps)

AAN model size (now 250 Mb)

Conclusions

If NN works - it’s a huge advance.

Advantages to date:
All tools , tutorials, guides, libraries, algorithms are free.

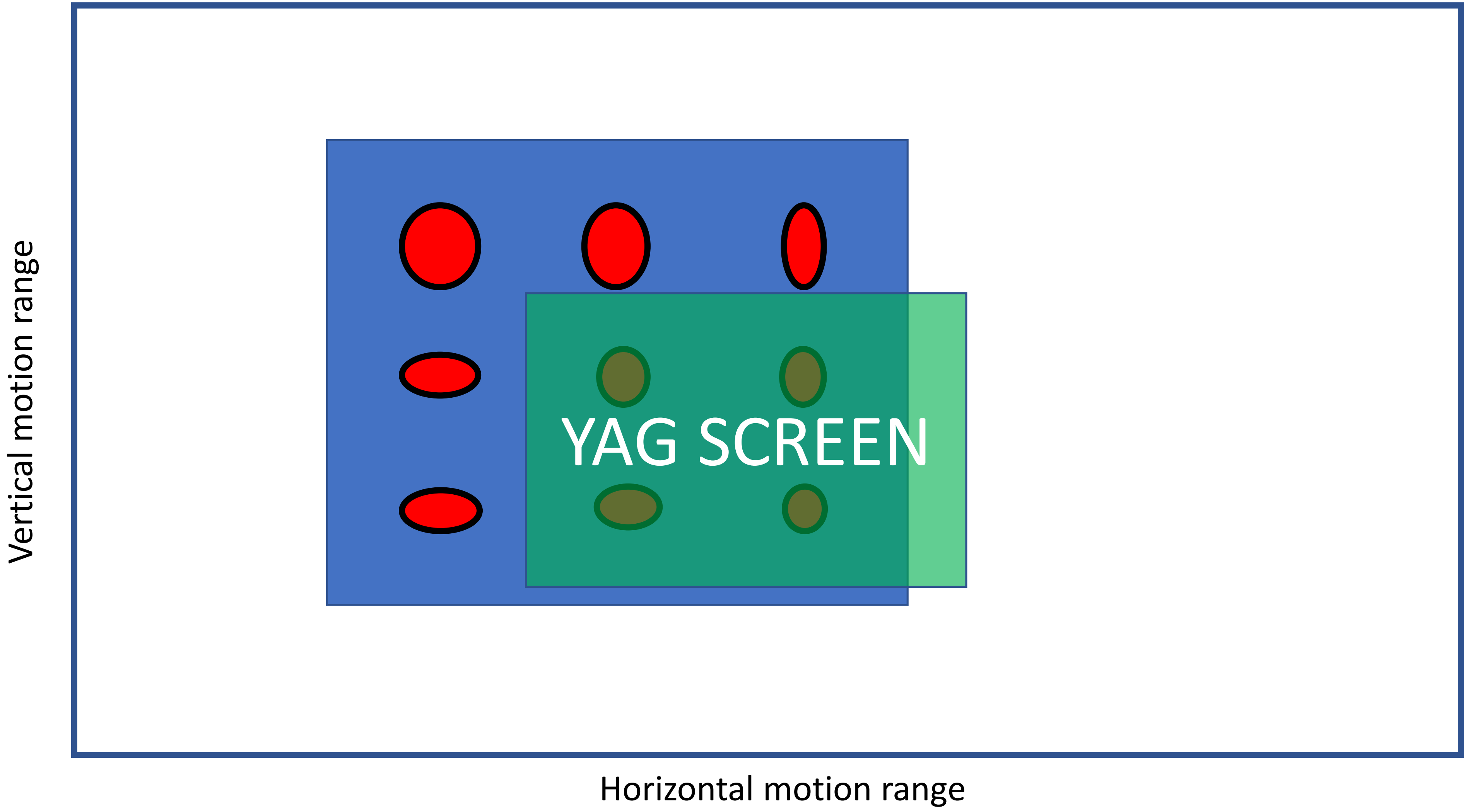
Bottlenecks to date:
Large time investment to tune and train the model.
Large hardware investment.
Quantity matters (CPU->GPU->HPC).

Machine training is long
Machine thinking is hard
(Great opportunity for student projects)

Thank you!

What pinholes am I looking at?

- Motion range - known
- YAG coords w.r.t. motion coords – known
- Pinholes coords (centered in YAG) w.r.t. motion coords - known

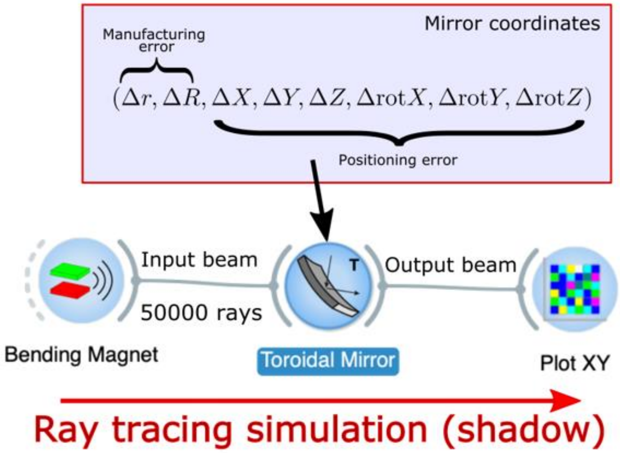


PS. Other ML projects done at Alba Synchrotron

MINERVA Beamline (Dominique Heinis)

Machine learning to model the behavior of a mirror subjected to manufacturing errors and misalignments (scikit-learn)

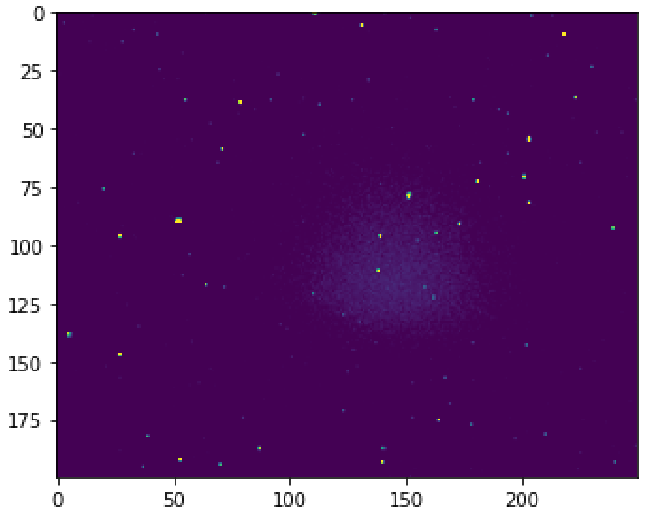
- learning using linear model (with polynomial features) to take into account optical aberrations and nonlinearities
- model calculates quickly the output beam (based on tensor product instead of ray tracing)
- model can be used to retrieve an analytical formula
- model allows numerical optimization (can be easily integrated in a steepest gradient like method)
- for the moment just one optical element but there is no theoretical constraints to extent it to a complete beamline

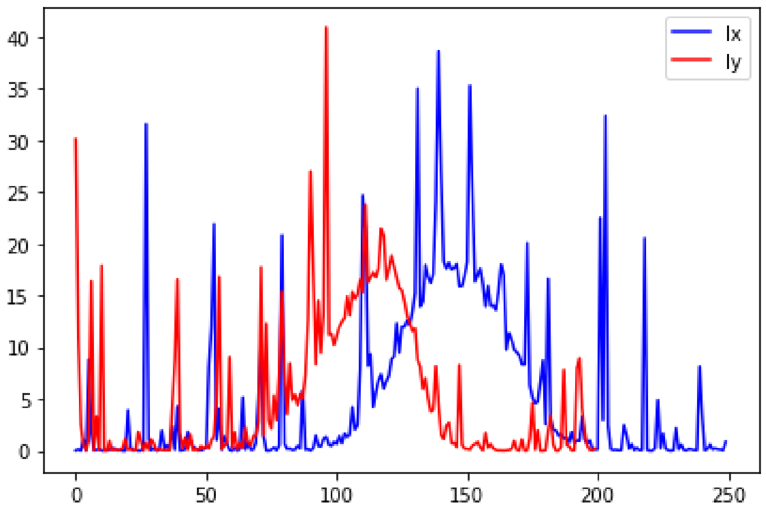


Beam Physics (Zeus Marti, Emilio Morales)

ANN to solve the measured orbit response matrix fit to avoid using the model (TF, Keras).

It does not work, it has too many elements (88x120x4) and knobs (112) and is too non linear, the training data is huge.
Instead it was possible to fit the inverse orbit response matrix, since it has much less elements (432) for the same number of knobs and it is much more linear.
It turned out to be so linear that a simple linear fit behaves as well as an ANN for the present precision of our measurements.




Ix
Iy