# Beam Tuning for ATF/ATF2 using Machine Learning

Masakazu Kurata

KEK

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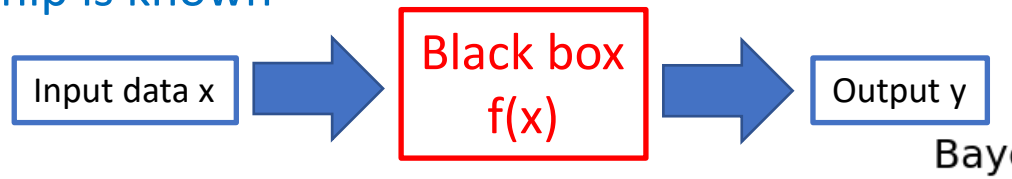
# Introduction

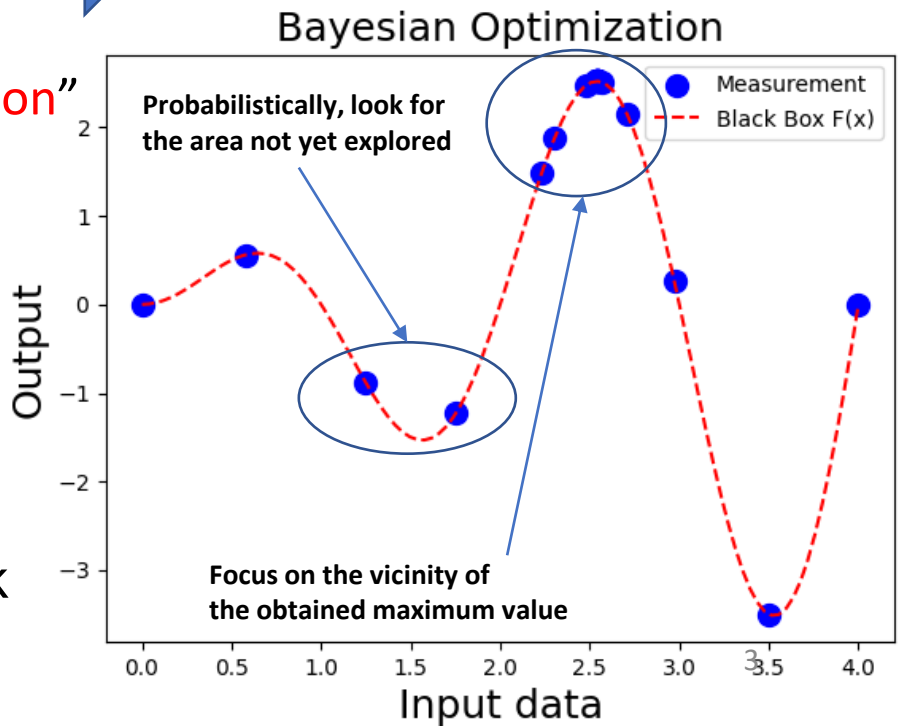
- What we want to do:
  - Beam optimization - Important points are
    - Effective accelerator parameter search for optimal beam
    - Simultaneous search of several parameters for the beam
    - Optimization without prerequisite knowledge or prejudice, bias

# Auto-tuning using Machine Learning

- Realization of automatic beam-tuning
  - Minimize the number of tuning parameter searches: Reduce tuning time
  - Simultaneous optimization of multiple parameters: Better tuning including correlation
- Optimization of the beam = "Black-box Optimization"
  - Looking for the global maximum in situations where only the input-output relationship is known




  - Auto-tuning using "Bayesian Optimization"



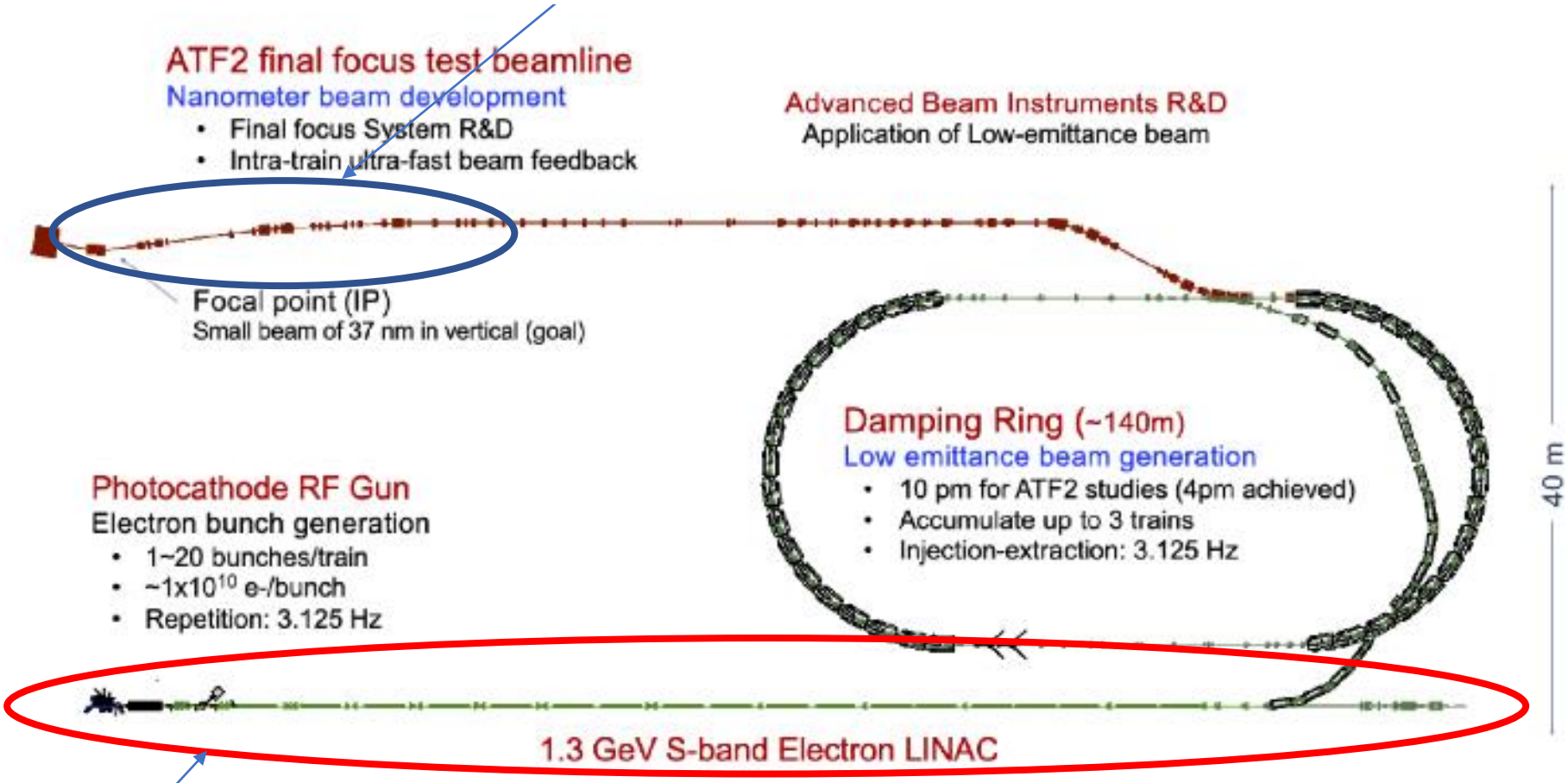

Using the trial results so far, predict
- Parameter space not yet explored
- Parameter space close to maximum value

and search efficiently

Do not need "training", like neural-network

# Bayesian Optimization at ATF

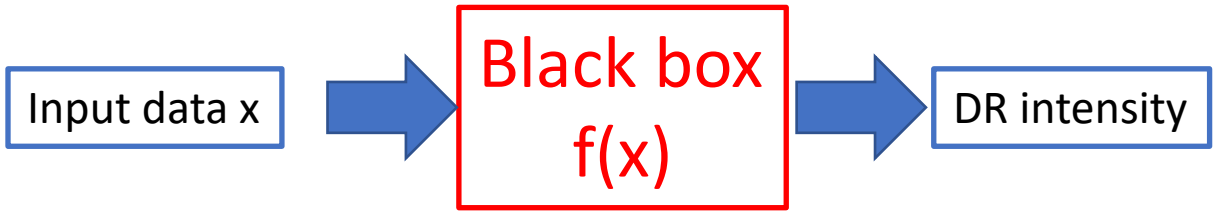
- **Knob scan**: to obtain small beam




- **Linac tuning**: to make beam intensity at DR as high as possible

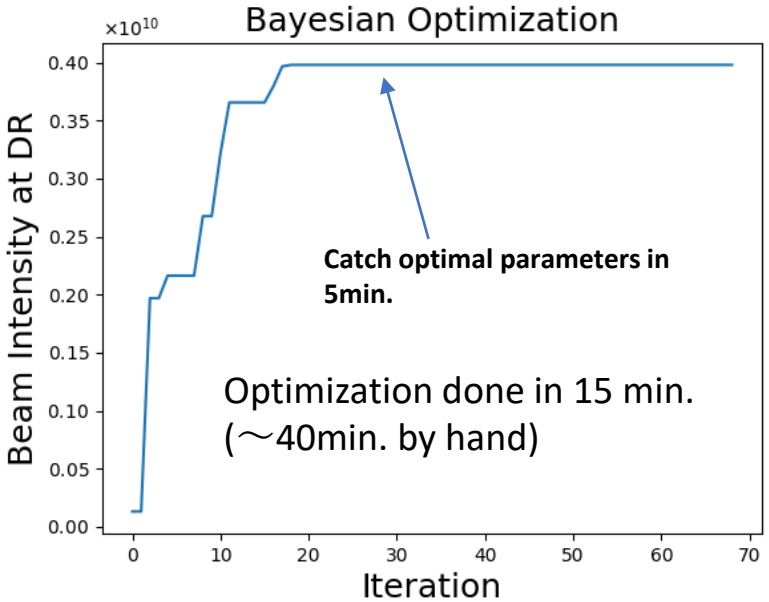
# Linac tuning

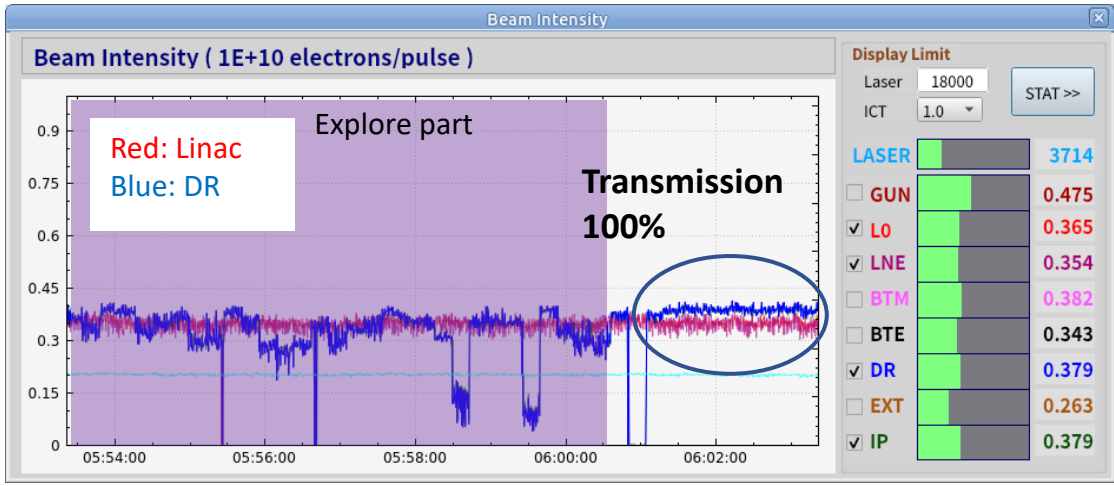
- Linac parameters are tuned to store high intensity beam at DR
  - Linac RF, timing
  - Steering magnets
  - Quadrupole magnets
- Simultaneous parameter search from 1D to 9D is possible
  - Any combination of the parameters on Linac can be used
  - It is difficult to do higher dimensional parameter search by hand due to combinatorial explosion



# One example

- Start at unknown status
  - Intensity at DR is not high: Transmission to DR is low
  - Optimize 8 Linac RF phases simultaneously
- After Bayesian optimization
  - Intensity at DR is recovered
  - About 50 iteration: ～15min.
  - Time consuming task is intensity measurement. Parameter set prediction is very light task

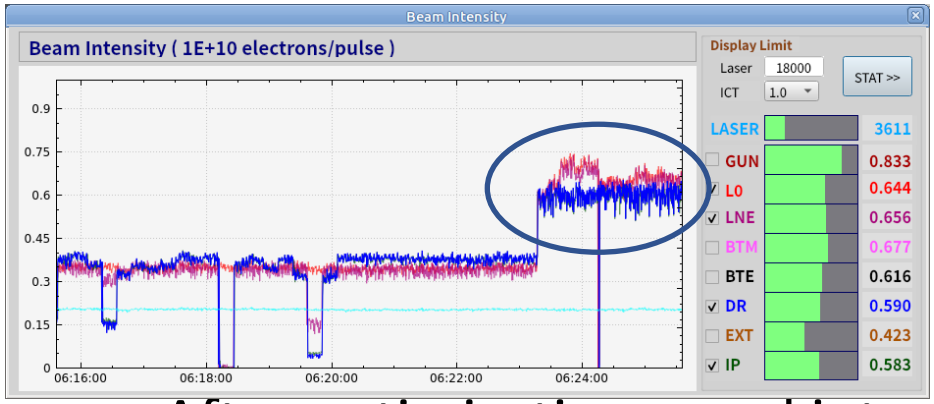


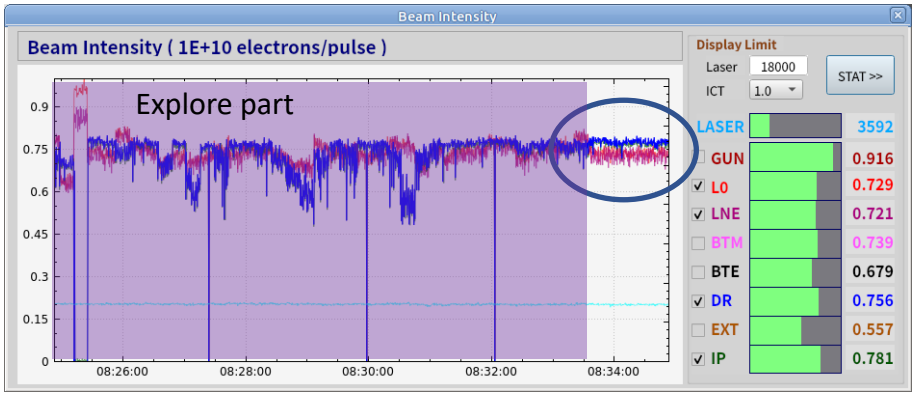
# High intensity case

- Just change gun laser power:
  - Optimal parameter is shifted, and stability reduced

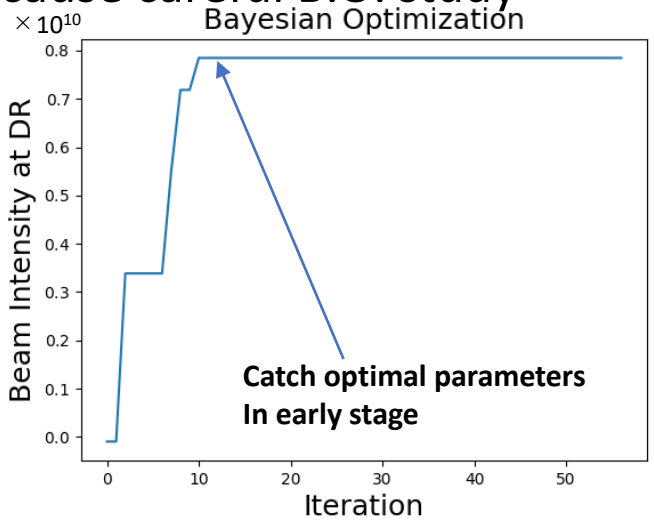
Before




After

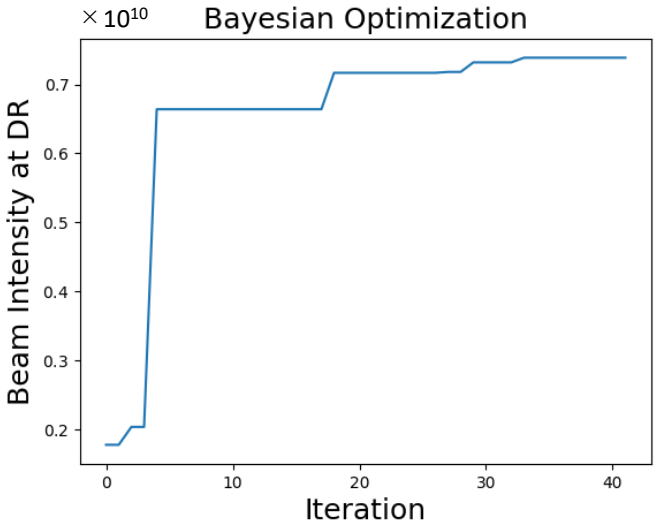



  - After optimization: good intensity for high current case
  - ～1.25h optimization, 5 cases of parameter search are performed
    - It takes a bit because careful B.O. study

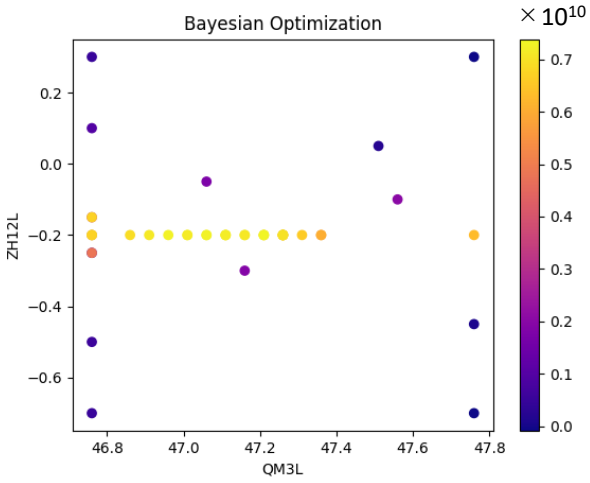


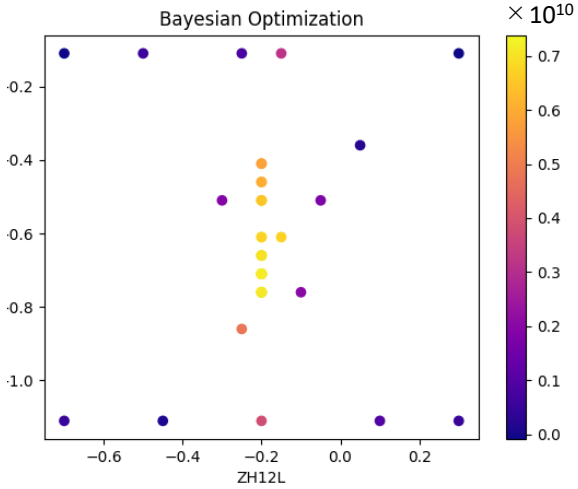
# Parameter scan example

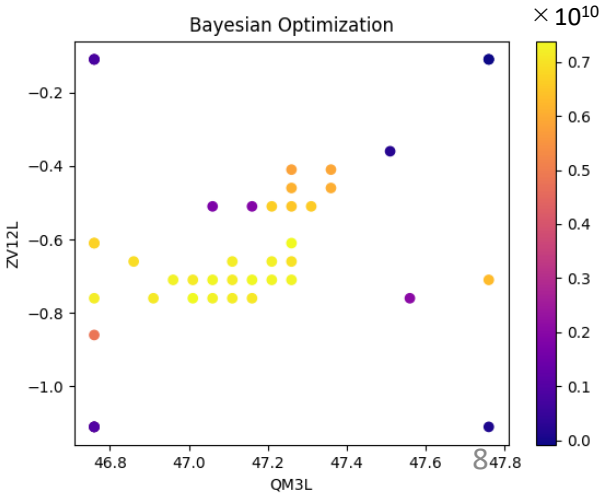
- 3D search with Q and H&V steers
  - Looks effective search can be realized




(QM3L, ZV11L, ZH12L)

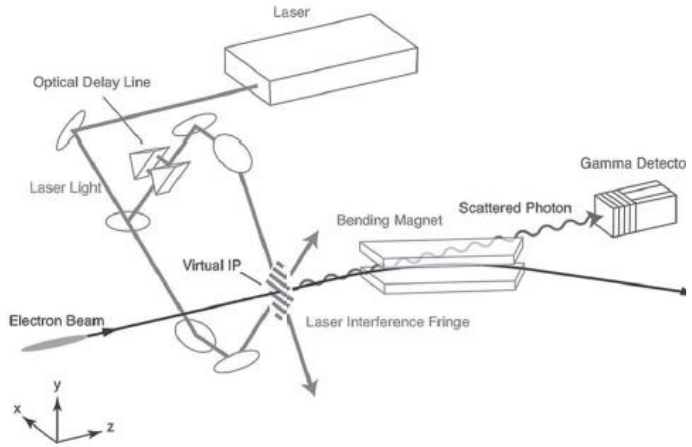


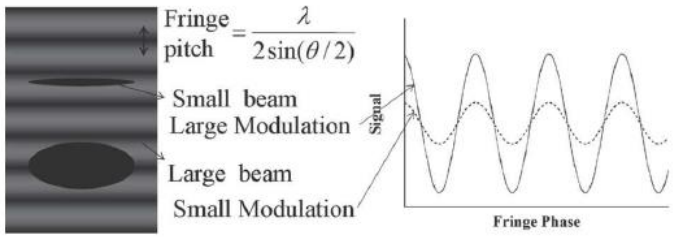



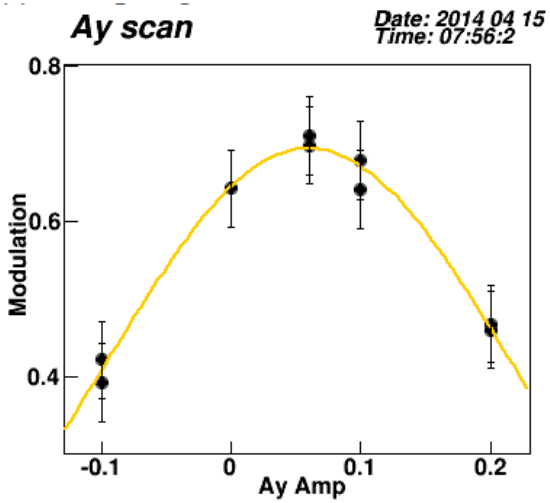
# Knob scan at ATF2 F.F.

- Chromaticity correction using 5 sextupole magnets
  - Create knobs to correct one parameter
    - Linear & non-linear knobs
  - Beam size is measured by the modulation of Compton signal




Large modulation ↔ Small beam



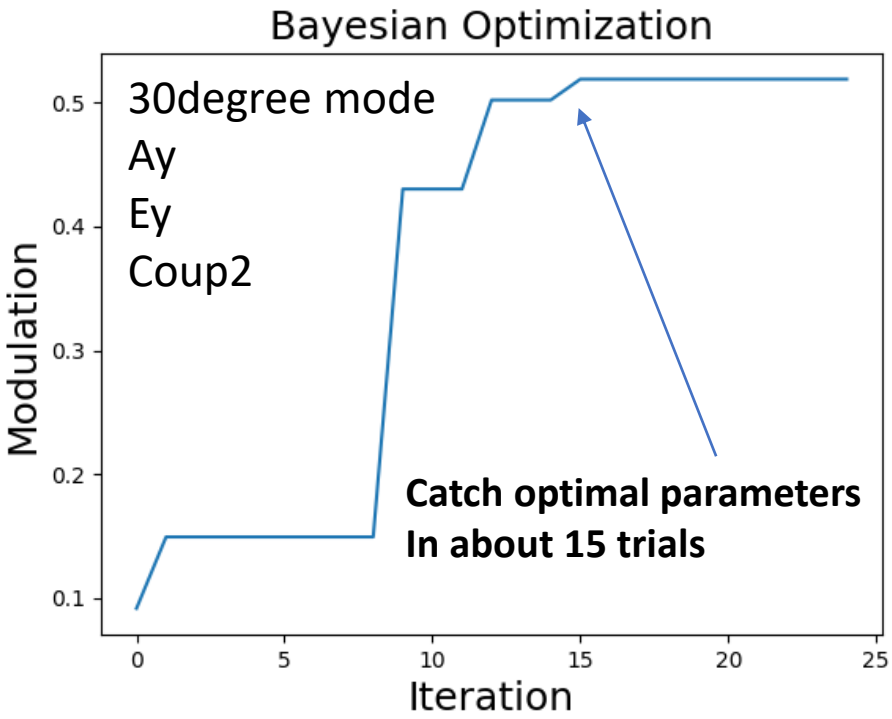

$M$ vs. knob strength
IPBSM 30 deg. mode

- Simultaneous knob search using B.O.
  - Effective search including correlation
  - Linear Knob + non-linear knob

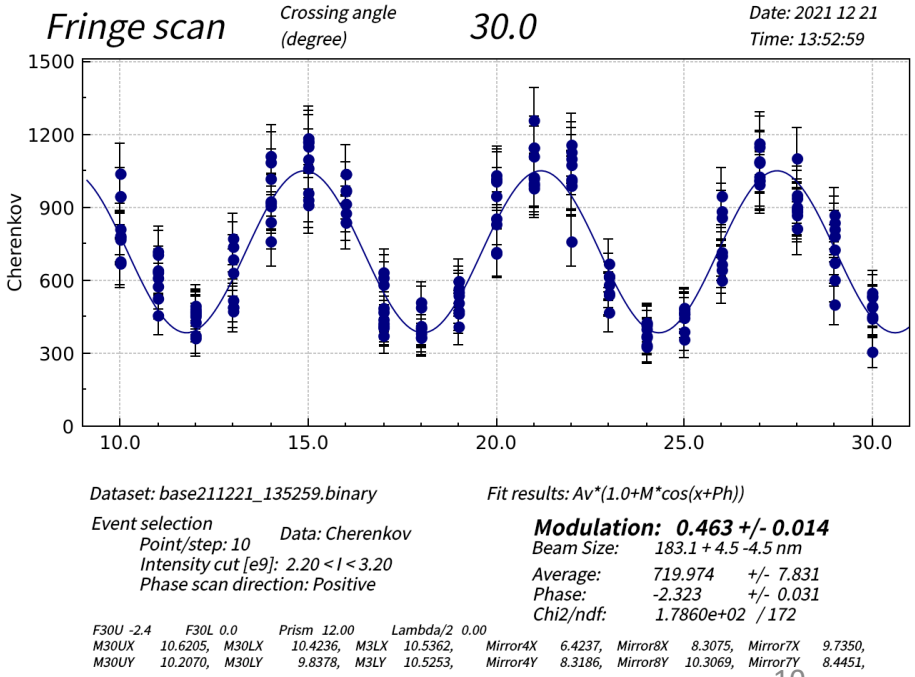
knobs x → Black box f(x) → Modulation

# B.O. using linear knobs

- Trial: optimization is performed by B.O. and compare the result with sequential linear knob optimization
- Bayesian Optimization: can catch the parameter set which has large modulation in ～15 iteration

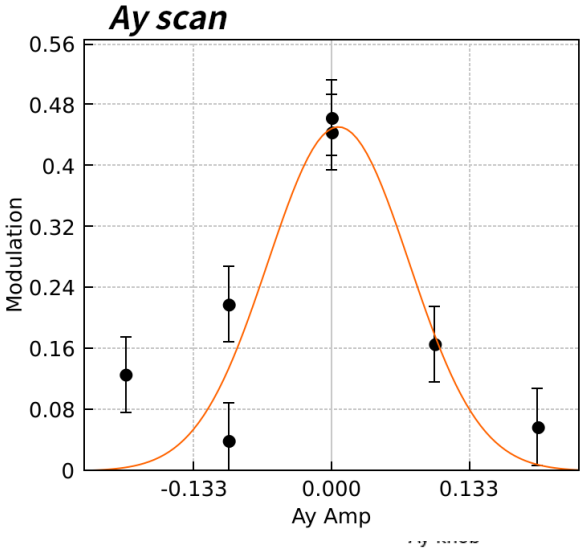



Sequential tuning result



# Comparison with sequential tuning

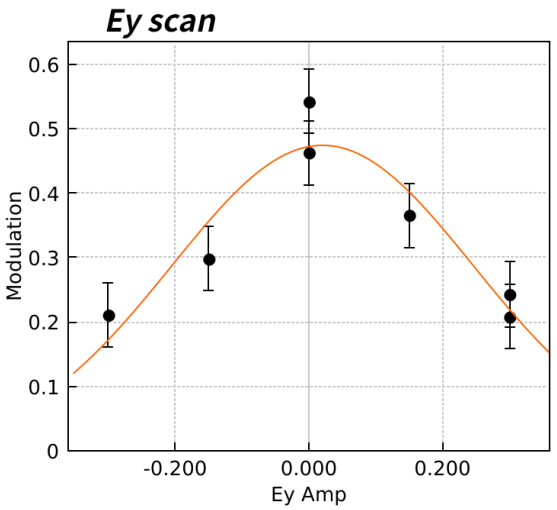
B.O. (Ay, Ey, Coup2)=(0., 0., -0.)




*Date: 2021/12/24 Time: 03:40:06*

*Fit results: A*exp(-((x-B)/C)^2/2)*
*Modulation: 0.452 +/- 0.036*
*Center: 0.006 +/- 0.009*
*Sigma: 0.068 +/- 0.007*
*Chi2/ndf: 1.3400e+01 / 4*

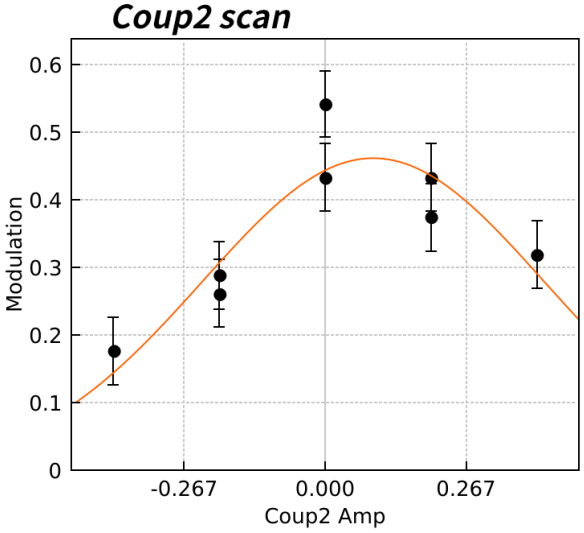
*Data file:*
*Ay_fringe_211224_034006.dat*




*Date: 2021/12/24 Time: 03:52:07*

*Fit results: A*exp(-((x-B)/C)^2/2)*
*Modulation: 0.476 +/- 0.032*
*Center: 0.019 +/- 0.020*
*Sigma: 0.226 +/- 0.023*
*Chi2/ndf: 4.7119e+00 / 4*

*Data file:*
*Ey_fringe_211224_035207.dat*




*Date: 2021/12/24 Time: 04:09:01*

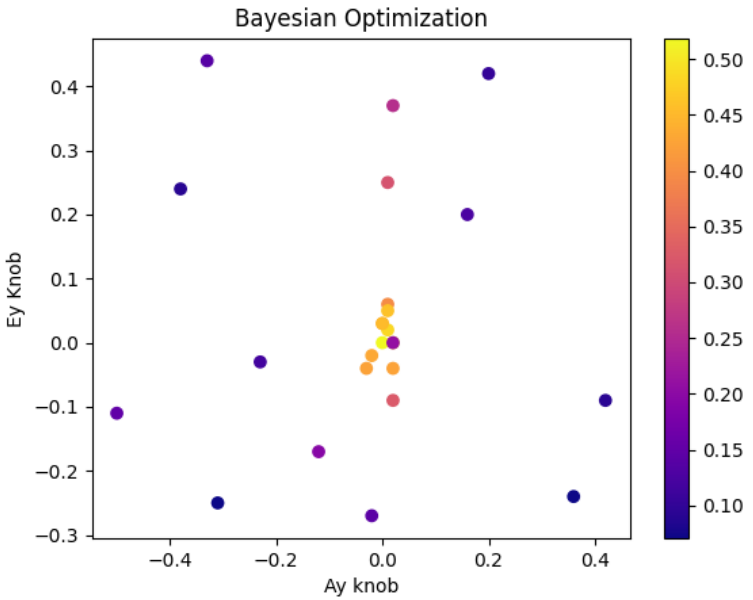
*Fit results: A*exp(-((x-B)/C)^2/2)*
*Modulation: 0.463 +/- 0.029*
*Center: 0.090 +/- 0.030*
*Sigma: 0.323 +/- 0.041*
*Chi2/ndf: 7.1006e+00 / 5*

*Data file:*
*Coup2_fringe_211224_040901.dat*

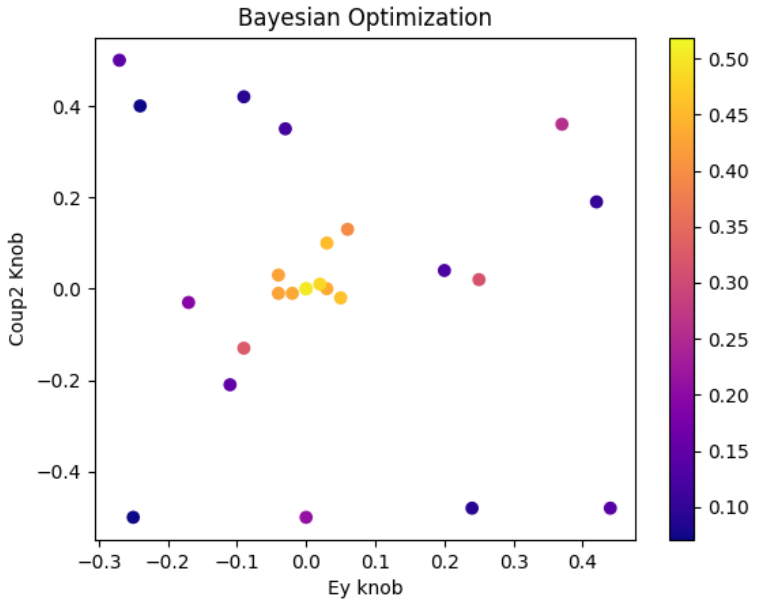
- Check using nominal each knob scan
- B. O. prediction is good agreement with nominal knob scans

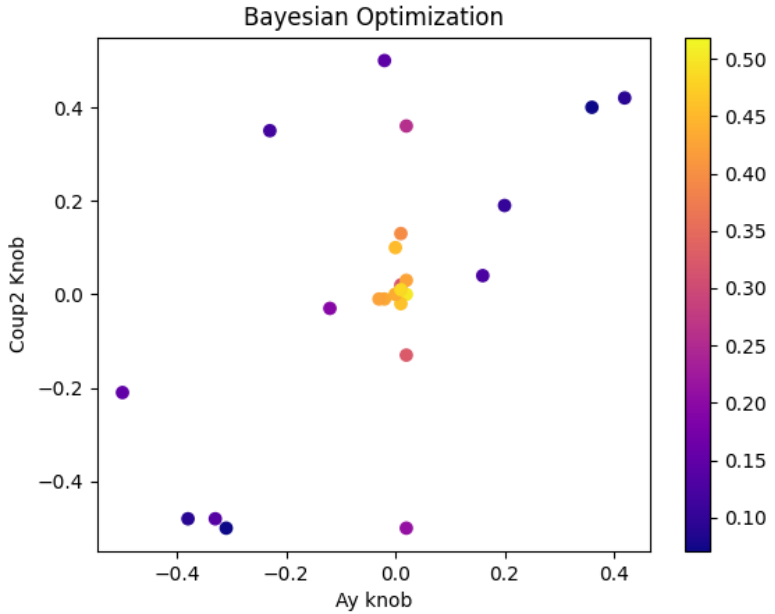
- 30degree mode
- Iteration: 24
- Domain: [-0.5, 0.5]

# How B.O. work




B.O. (Ay, Ey, Coup2)=(0., 0., -0.)



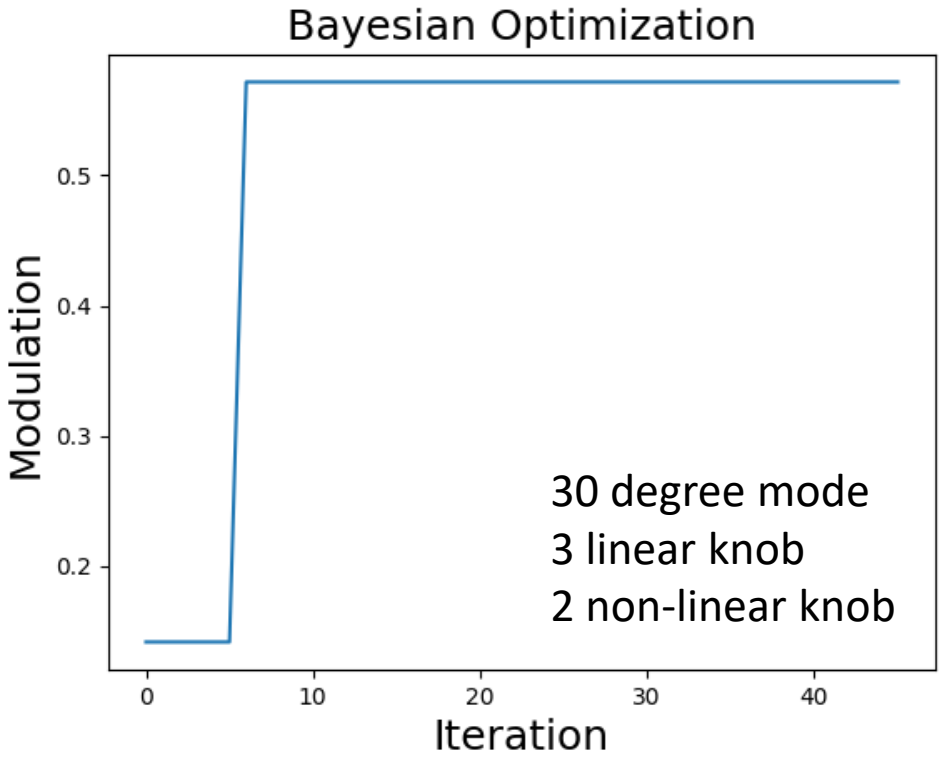



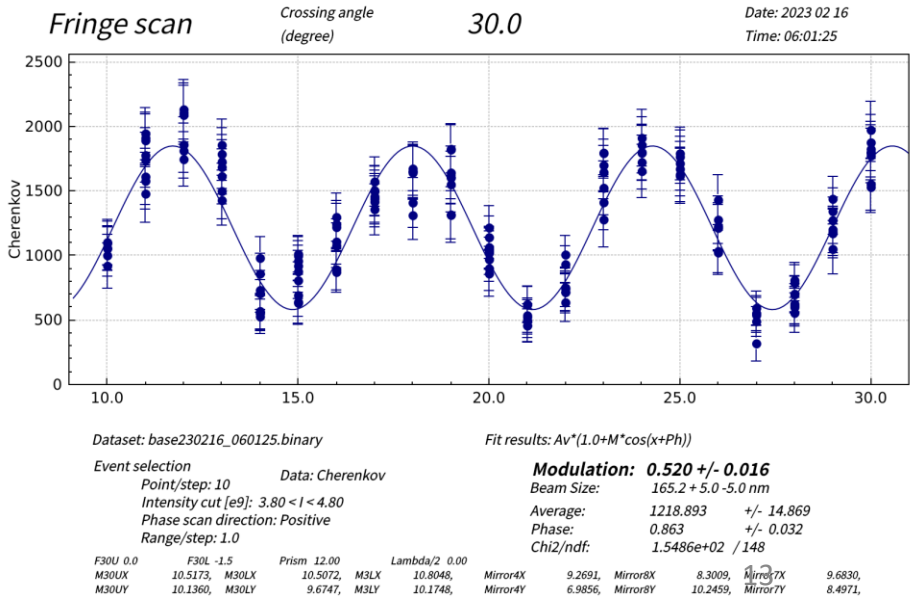

- B.O. can focus on around (0,0,0) search
- Probabilistically, look for other parameter sets

- 30degree mode
- Iteration: 24
- Domain: [-0.5, 0.5]

# B.O. with Linear & non-linear Knobs

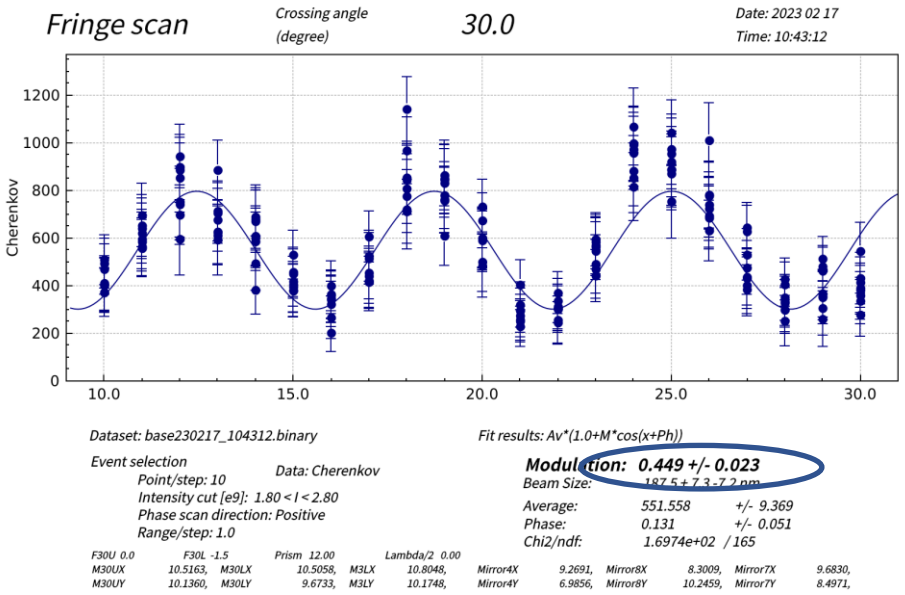
- B.O. with 3 linear knobs and 2 non-linear knobs
  - Linear: Ay, Ey, Coup2
  - Non-linear Y22, Y24
  - Optimal parameters make modulation ～0.57
- Sequential tuning: modulation 0.520



# Problems

- Measurement instability confuses optimization
  - After optimization, check the modulation again
  - Are these obtained parameters really optimal?
  - Some measurements with same parameter should be necessary for stability




- Optimization time should be reduced
  - In early stage, it is almost same as random search
  - Therefore providing some hints in early stage may be helpful

  e.g.) only 1 parameter is changed for next measurement

  give some sets of the parameter set, and start gaussian process prediction

# Summary and outlook

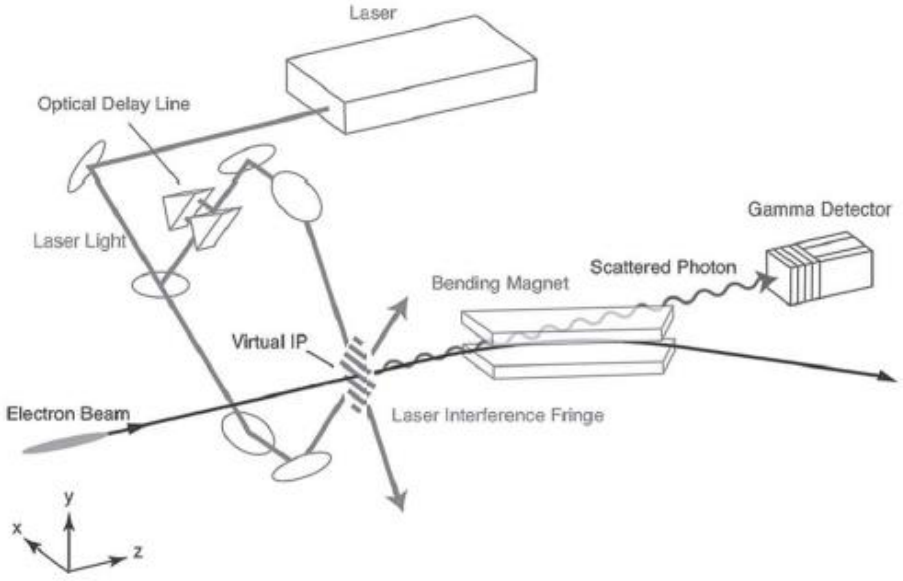
- Basically, Bayesian optimization works well
  - Effective parameter search can be realized
- Tune of estimation
  - Tune evaluation function, consider the optimization target
  - Optimization time should be reduced
  - Choose optimal parameter set with robustness
- About knob scan, parameter search with linear and non-linear in 174° tuning should be tried for small beam
- Bayesian Optimization can be introduced into many other tunings
  - Orbit tuning using BPMs
  - Beam optimization on the screen
  - etc.

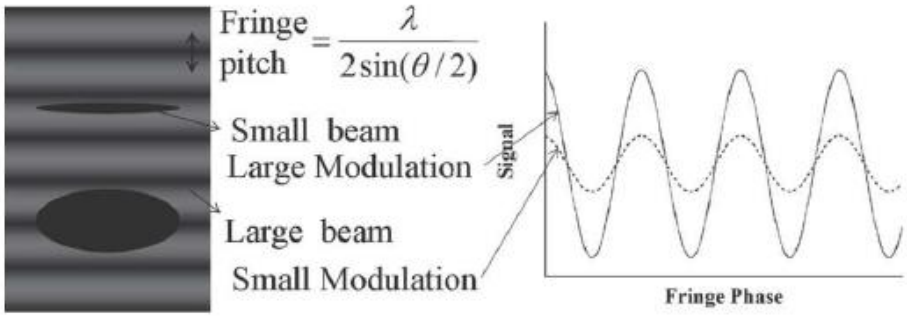
# ビームサイズ測定

- ATF2ではビームは1本: サイズ測定に別な技術が必要
  - ビームをレーザー干渉縞にぶつけコンプトン散乱光を見る
  - 当たった縞の位置によって散乱光の強度は変化

  ⇒分布が波のようになる
  - ビームサイズによって波の振幅が変化

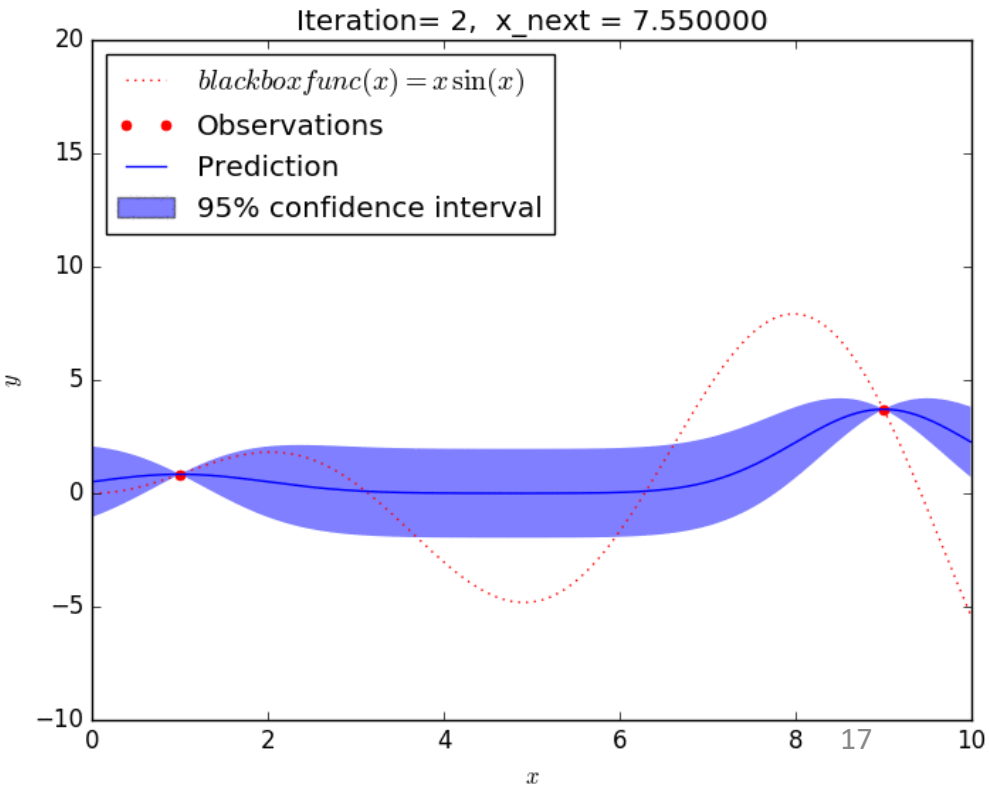
  ⇒ビームサイズが測定可能



# Bayesian Optimization

- Effective parameter search with trial as small number as possible
  - Predict probable parameter set using previous measurements
    - Prediction based on the Gaussian process
  - Can search for global maximum(minimum) of the black box function




- The range that has not been searched much
- A range close to the maximum value already known

Select such kinds of parameter set effectively