Machine Learning at KEK

For beam tuning

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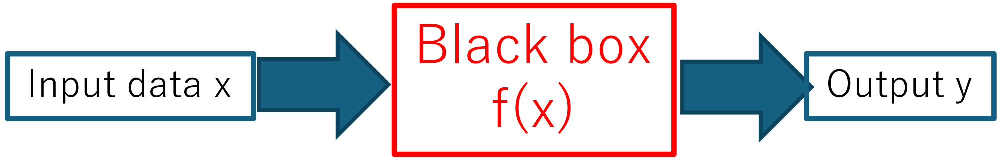
Auto-tuning using Machine Learning

- 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 point in situations where only the input-output relationship is known



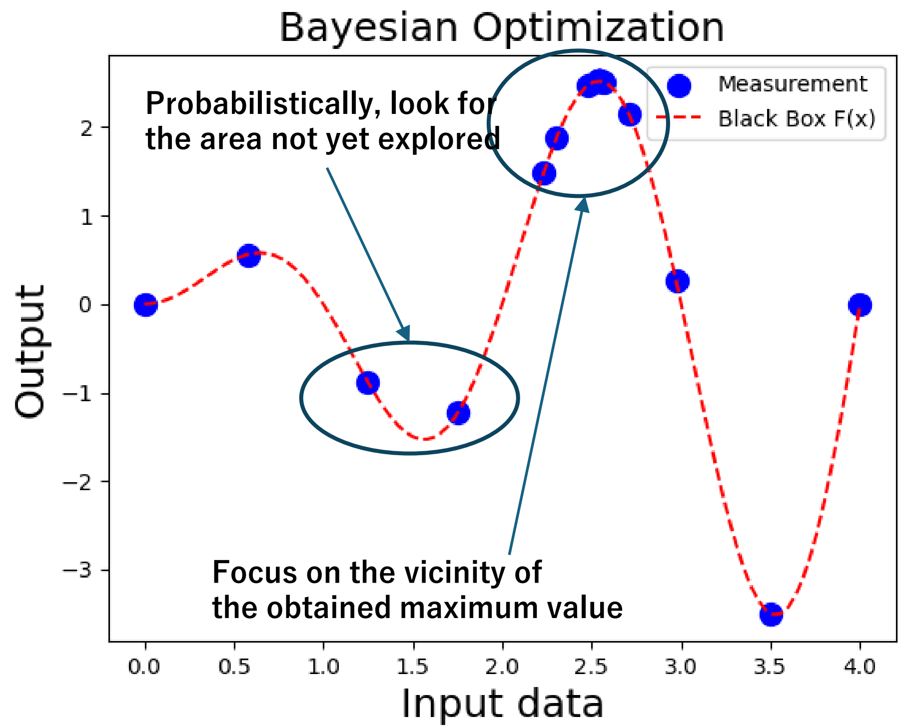
  - Auto-tuning using "Bayesian Optimization"

Using the trial results so far, predict

- Parameter space not yet explored
- Parameter space close to maximum value

and search efficiently

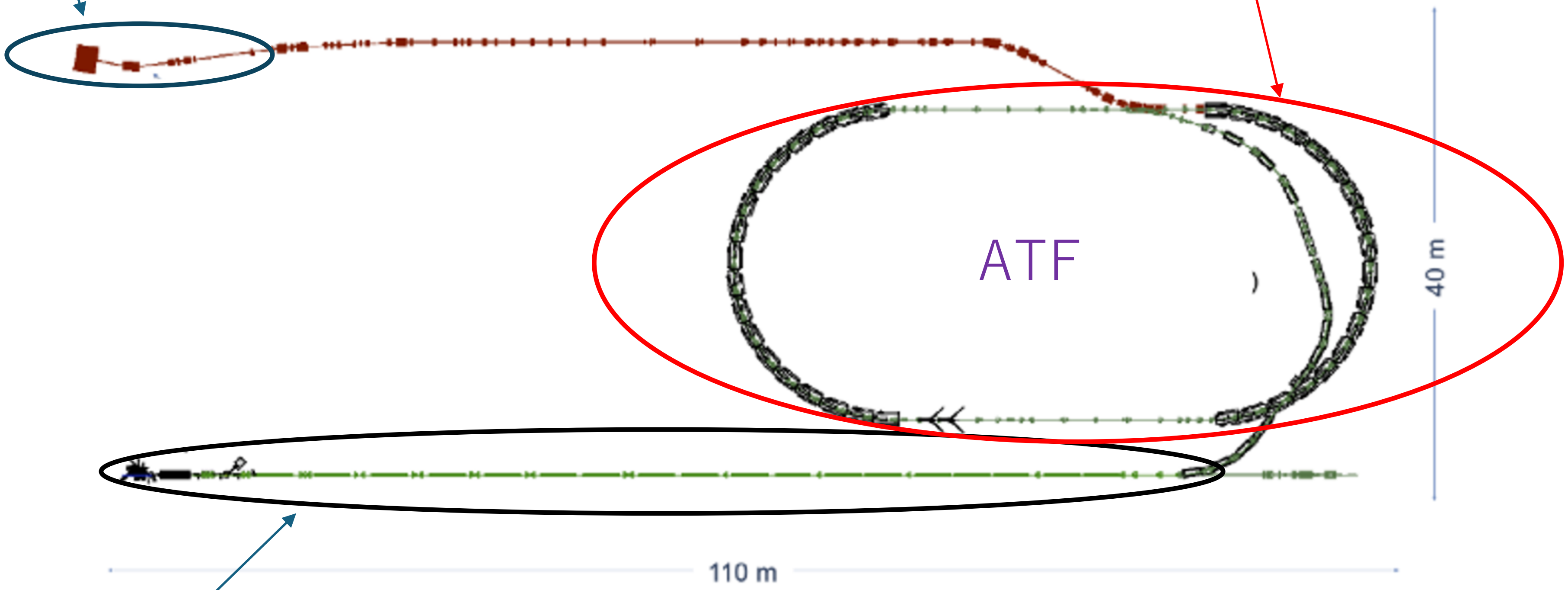
Do not need "training", like neural-network



Machine Learning @ATF

- Final Focus: Nano-beam tuning for the ILC

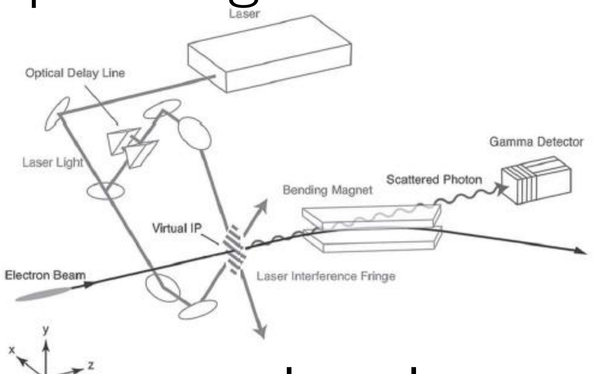
- Damping ring: tuning for small emittance
  - New feature



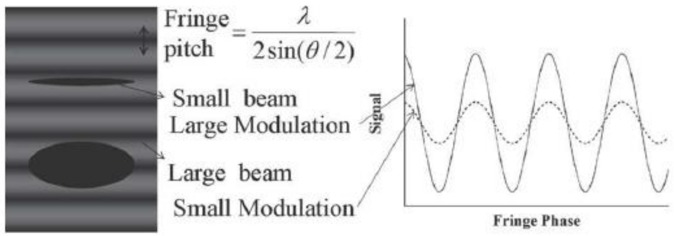
- Linac: Beam transportation to Damping ring

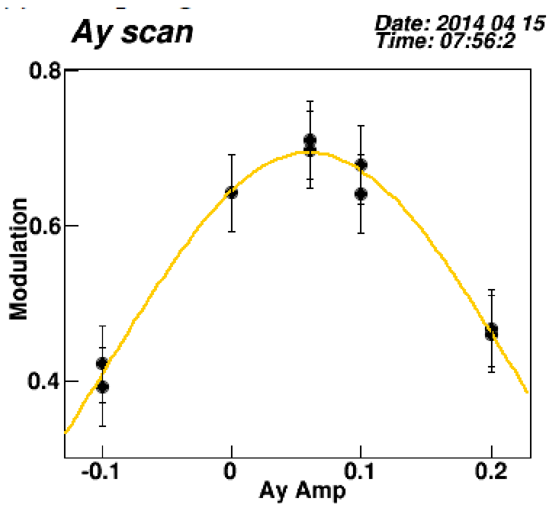
Knob scan at ATF2 F.F.

- Chromaticity correction using 5 sextupole magnets for small beam
  - 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 for future)
  - Problem: robustness of the optimization

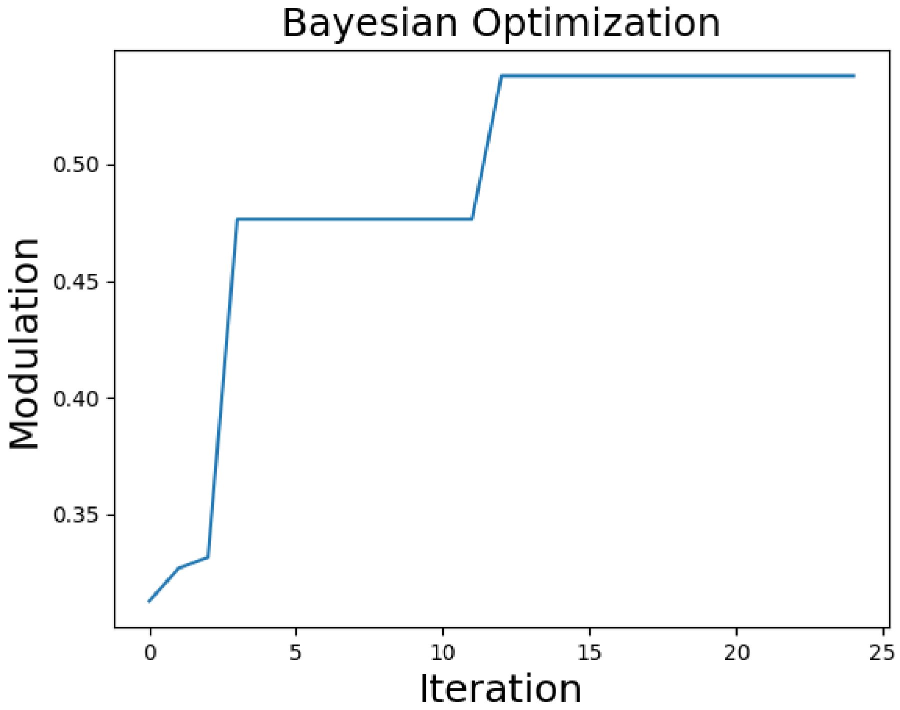
knobs x → Black box f(x) → Modulation

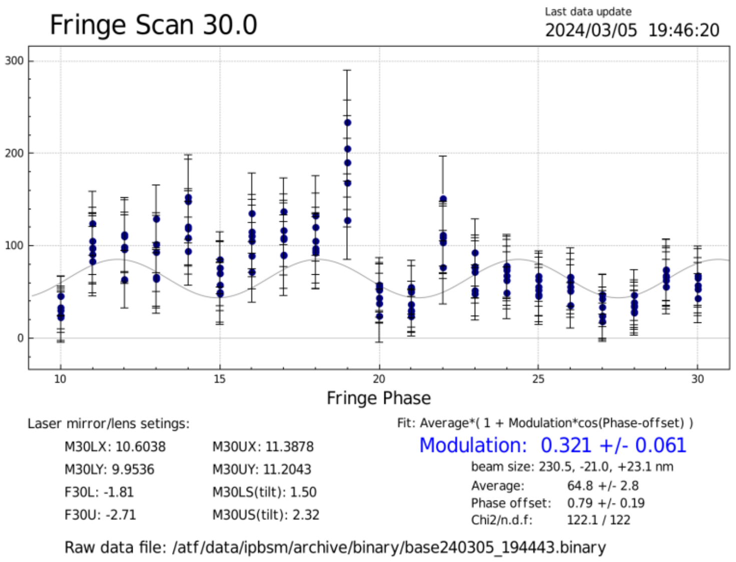
Strategy for robust optimization

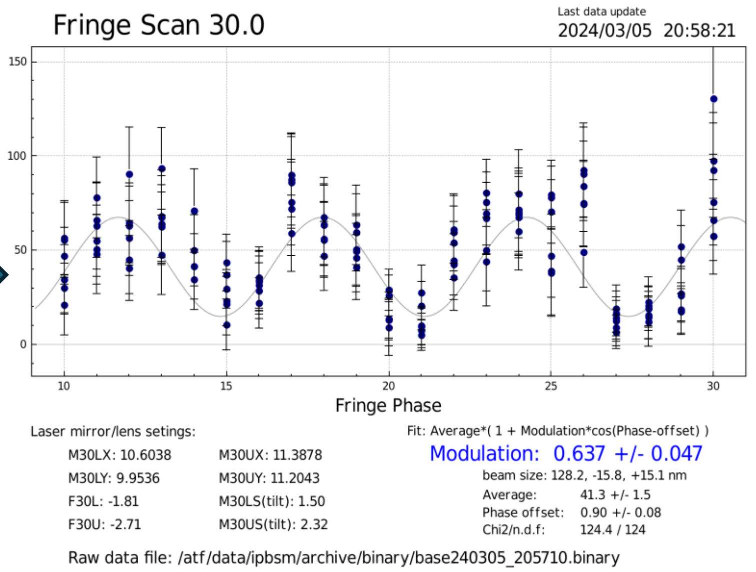
- In previous studies, optimization suffered from measurement fluctuation
  - During optimization, it looks OK ⇒ after that, is it really optimal??
  - No robustness…
- So, introduce some technique & treatment
  - Modulation was measured up to 3 shots with same parameter set
    - If highest modulation ever was observed, try same measurement up to 3 times
    - Suspicion of “lucky” measurement
    - To save time, do these step above only for the highest value ever
  - For the first few measurements, parameters set systematically and intentionally
    - e.g.)
      - 1: (Ay, Ey, coup2) = (0, 0, 0)
      - 2: (Ay, Ey, coup2) = (0.15, 0, 0) (just 5% of domain interval)
      - 3: (Ay, Ey, coup2) = (0.0, 0.15, 0)
      - 4: (Ay, Ey, coup2) = (0.0, 0.0, 0.15)
    - After those, do normal Bayesian optimization

Results

- Linear knobs: Ay, Ey, Coup2 & 30degree mode
- Iteration: 24
- Optimization: (Ay, Ey, Coup2)=(0.03, 0.05, 0.17)
- After optimization: check modulation by independent measurement
  - 0.32 ⇒ 0.64, looks correctly optimized
  - Optimization looks robust as for this measurement

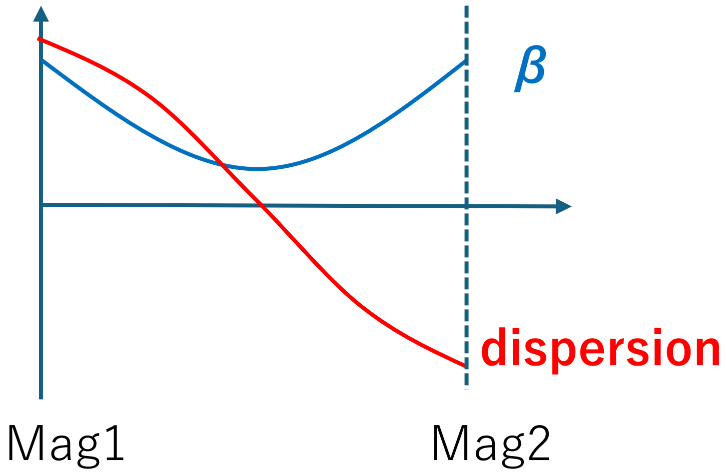






DR tuning for small emittance

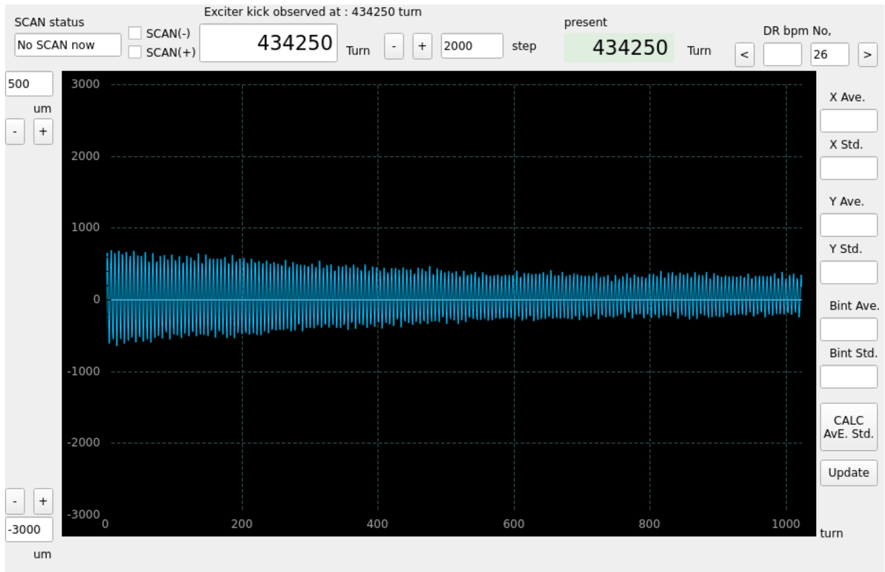
- Minimization of emittance @DR will directly lead to small beam size @FF
    - However, correlation of each component at DR is very complicated
- Tune SF series or SD series trim magnets to obtain small emittance @the profile monitor(XSR)
- β and dispersion correction using ML
    - Tuning magnet pair with phase advance π
        - β : correction in same direction of magnets' strength
        - η : correction in opposite direction of magnets' strength
    - Include consideration of correlation & higher order effect
- 4 pairs of magnets are tuned simultaneously
    - Both SF and SD trim coils sequentially

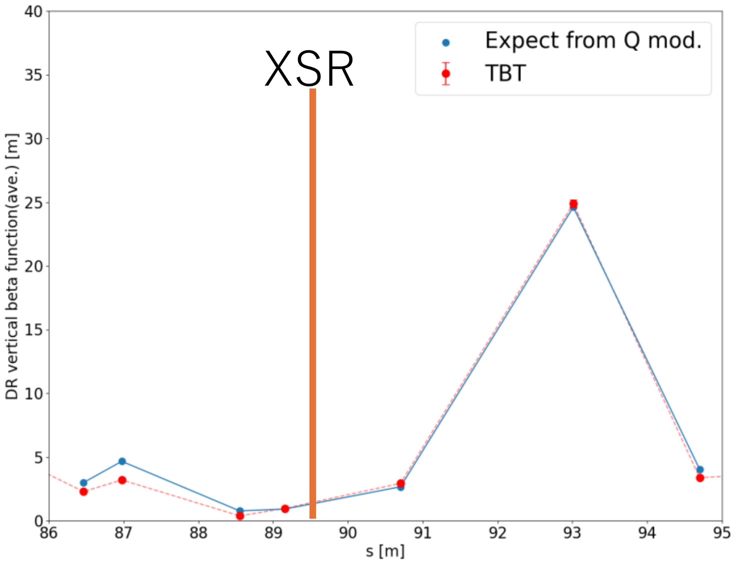


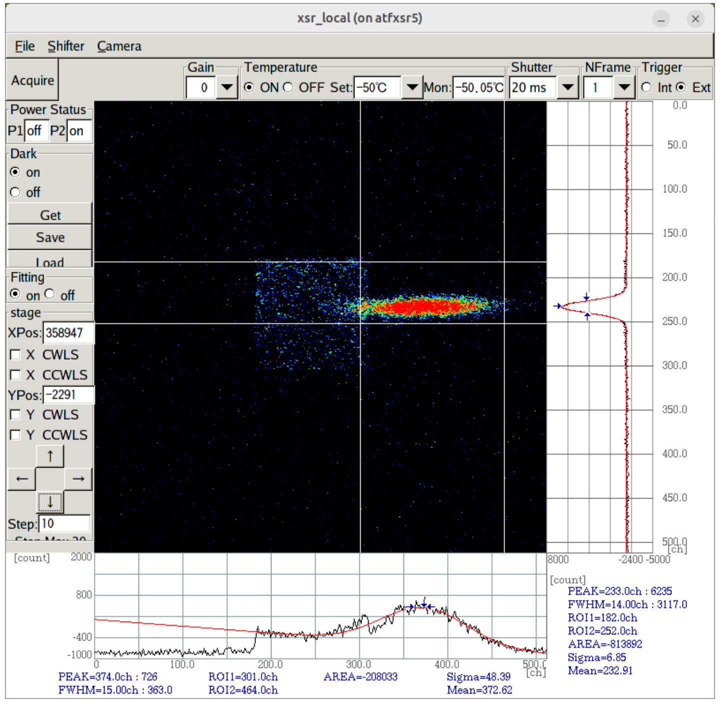
Emittance optimization

- Emittance: $\sigma_y = \sqrt{\beta \epsilon_y} \rightarrow \epsilon_y = \sigma_y^2 / \beta$
  - Needs simultaneous optimization of both β & σ_y

    → Online estimation of β and σ_y is essential
- β estimation: From Turn-by-Turn bpm measurement
  - Now, looks working
  - Needs detailed study for scale factor estimation from FFT amp. to β
- Beam size measurement: From XSR image

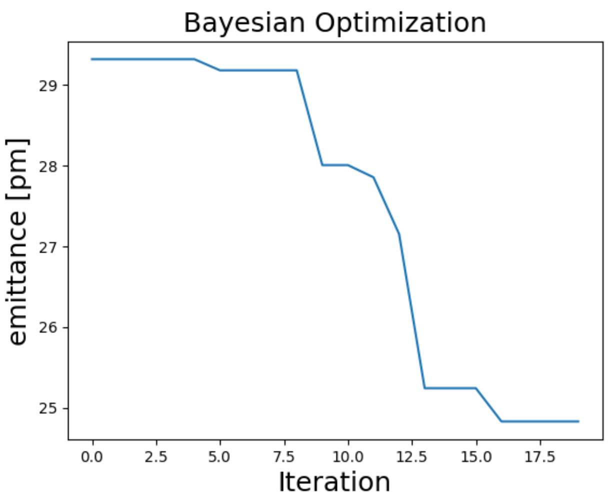


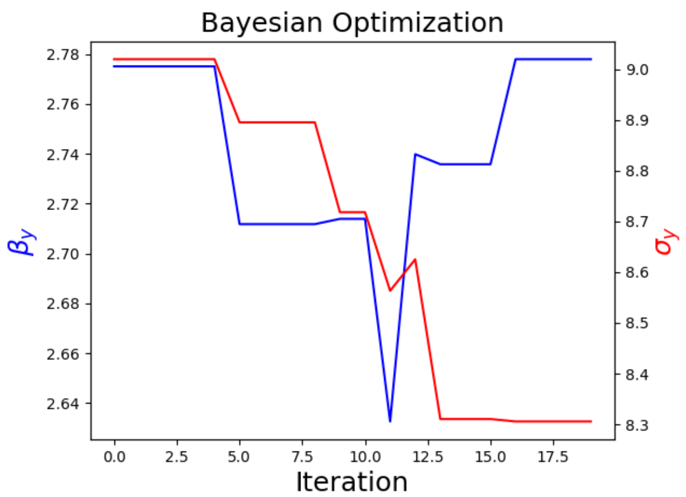


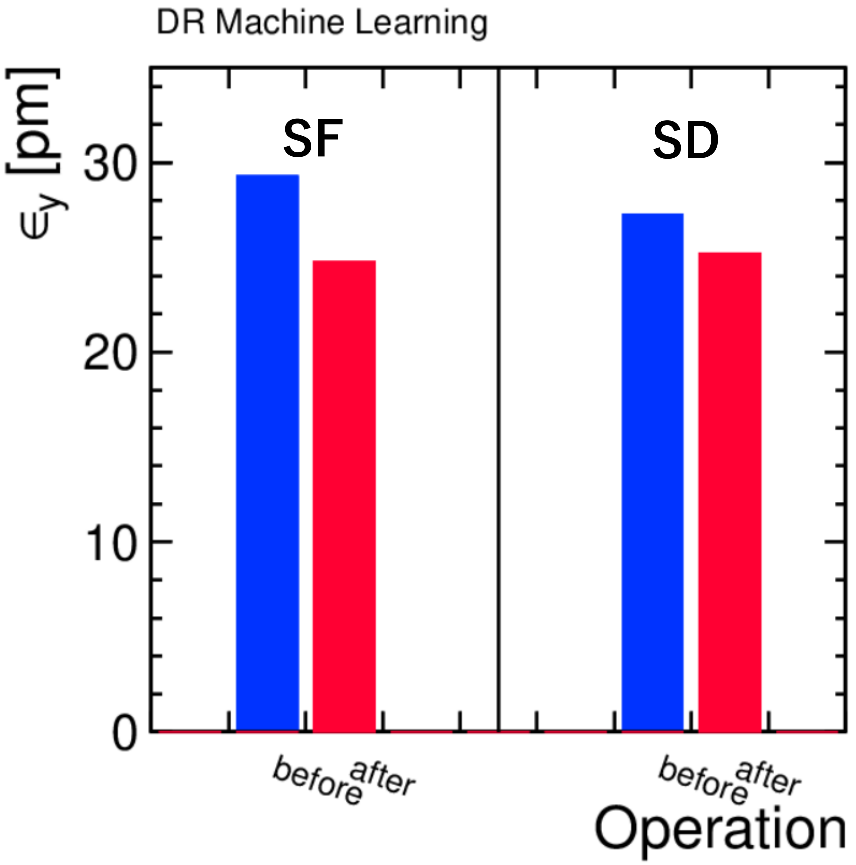


Preliminary Result of small beam size tuning at DR

- Beam tuning using ML
  - Tune SF magnets using ML
  - Tune SD magnets using ML
- Emittance: ~29 [pm] ⇒ ~25 [pm]
- Emittance became smaller successfully
  - Just started to conduct stable optimization





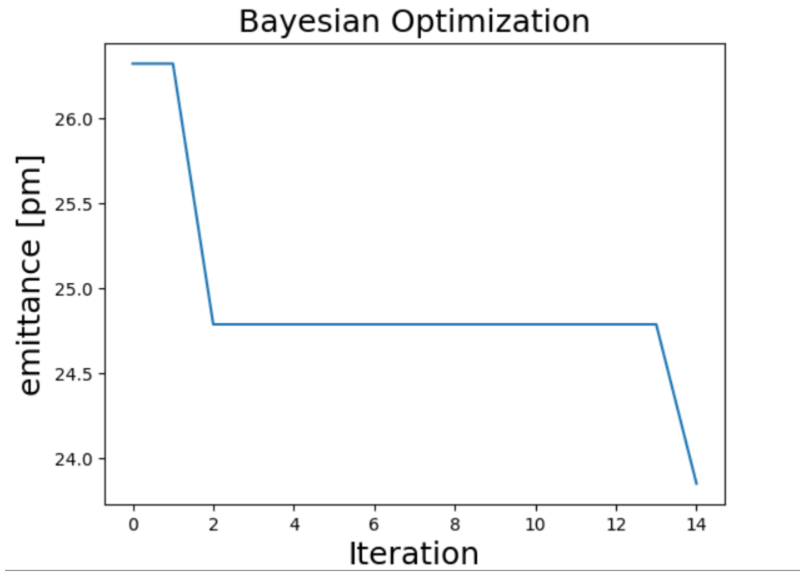


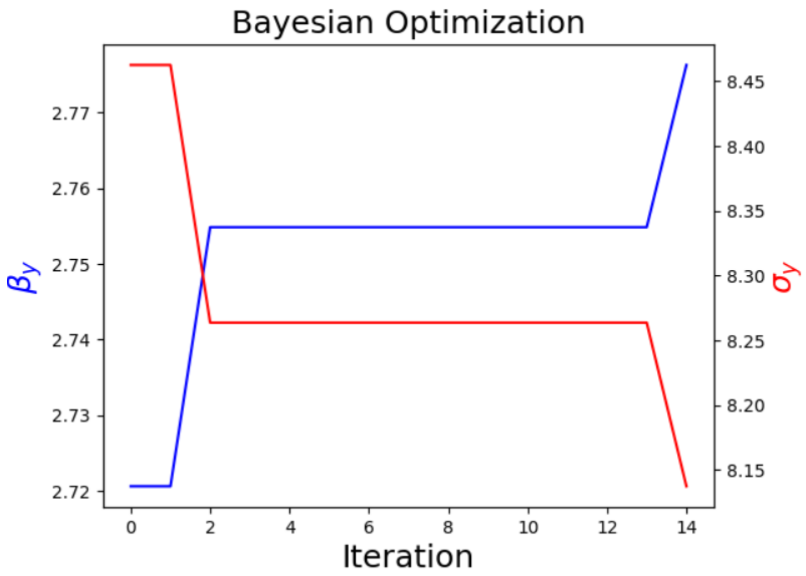
- Result of ML(SF tuning)
  - Optimization was going well
  - Realize β_y: large σ_y: small optimization

Possibility of emittance minimization

- Any set of the magnets will be able to try for optimization
- Example of different magnet set: just a TRIAL
  - Just selecting magnets without leading knowledge
  - Just choose 2 magnet pairs with phase advance of $\pi/2$
  - More reduction of the emittance could be obtained after previous page's result

- Emittance:
  27⇒24 [pm]
- Huge room to be optimized



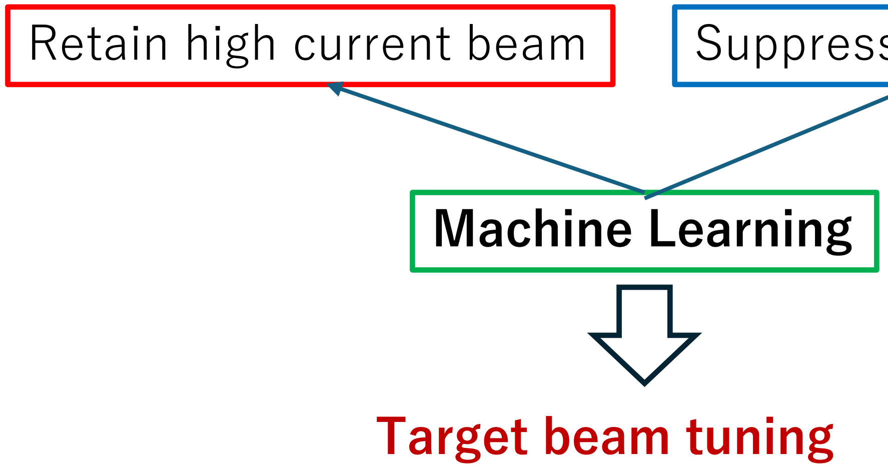


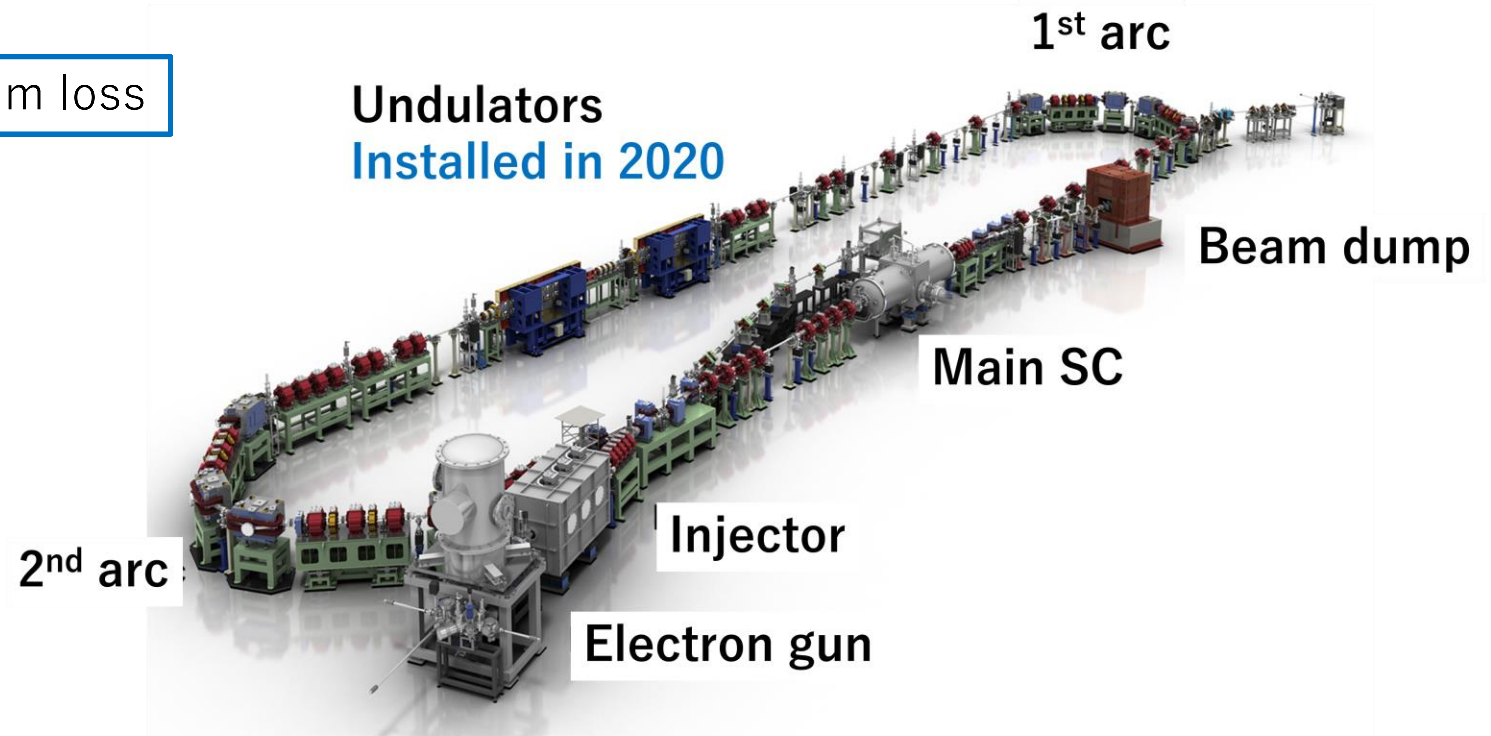
- Not yet reached a singularity…
  - Need the knowledge for drastic improvement by human
  - We need your help for such knowledge

Other ML application for beam tuning

- Compact ERL (cERL)
  - cERL also explore the possibility of auto-tuning for high current operation with ML
  - Target: high current CW operation while suppressing beam loss
    - Beam loss leads to severe radiation due to CW operation

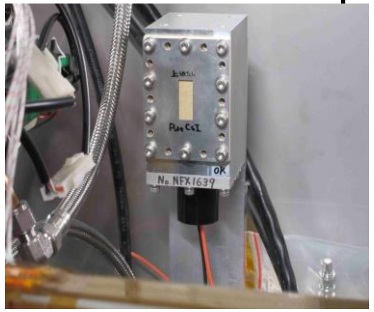
    → go to termination
  - Realize beam tuning aiming for compatibility between the two conditions





Optimization while avoiding IL and corruption

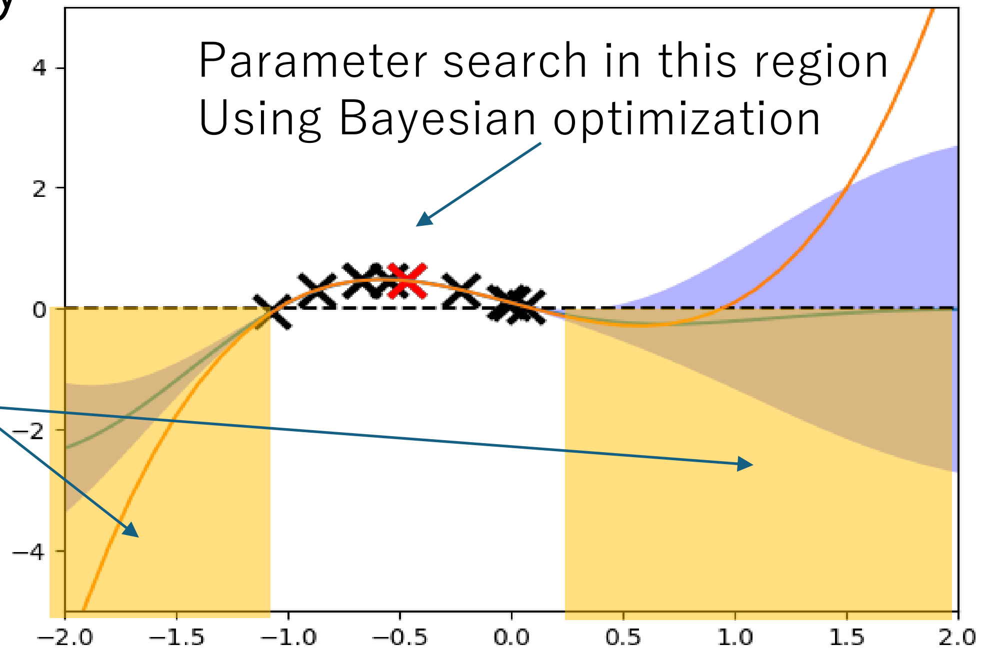
- Find loss: watching by loss monitors



Loss monitor on the beam line

Loss monitor undulator section

- If the beam are lost during ML, PMT with HV near the loss point can lead to IL, or be BROKEN
- Therefore, optimization while avoiding “dangerous” parameter searches
- Now applying the algorithm to automatically estimate the ”safe” parameter space
- And then, do Bayesian optimization within that parameter space



Do not watch this region
If these areas are the region with IL

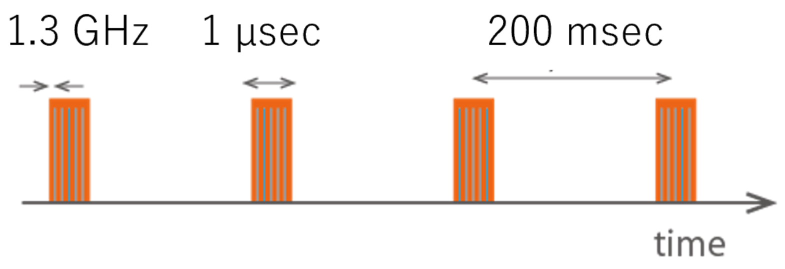
“Safeopt”

F. Berkenkamp, A. P. Schoellig, A. Krause, Safe Controller Optimization for Quadrotors with Gaussian Processes in Proc. of the IEEE International Conference on Robotics and Automation (ICRA), 2016, pp. 491-496.

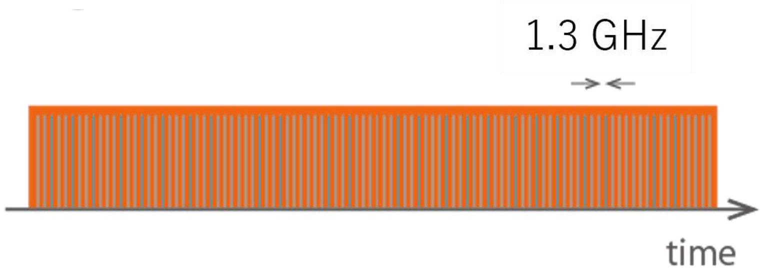
Beam tuning @cERL

- Tackling radiation level reduction: successive trials of both
    - Beam & collimator tuning in burst mode ⇔ Beam operation in CW mode
- Equipment to struggle beam loss:
    - **Loss monitors** - located anywhere on the beam line
    - **Collimators** - at the entrance & middle of the merger

Burst (5Hz)

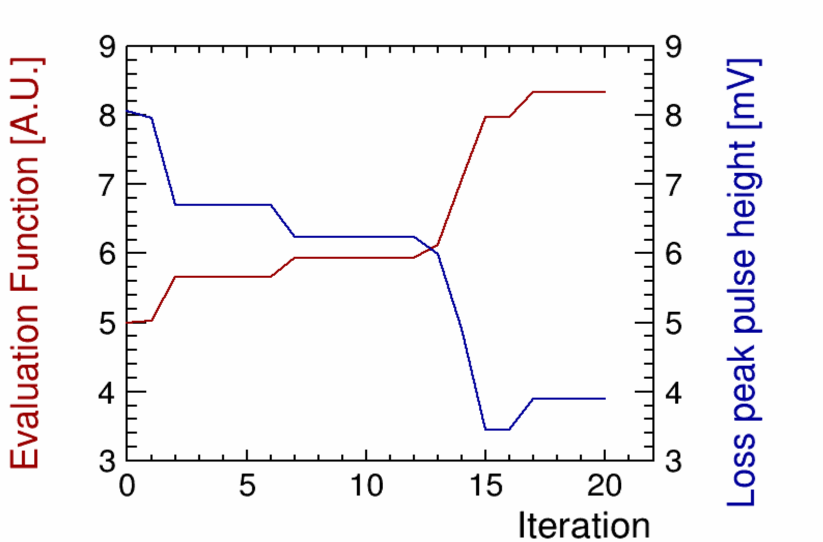


CW

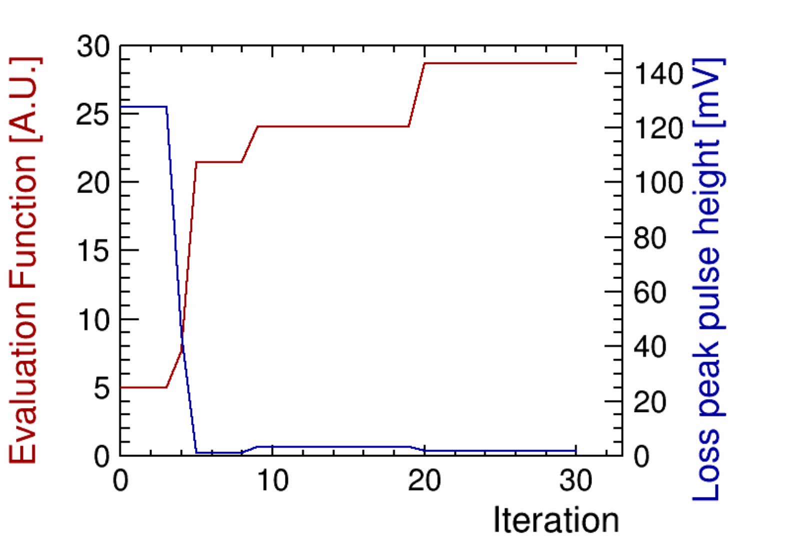


ML optimization

- Dedicated design of evaluation function is essential
  - Realization of both loss suppression & high beam current
- Machine learning tuning in burst mode
  - Choose Q & steer magnet's sets to suppress loss at a loss monitor to be controlled
  - 2 collimators optimization at the same time
- Well optimized under loss signal suppression condition



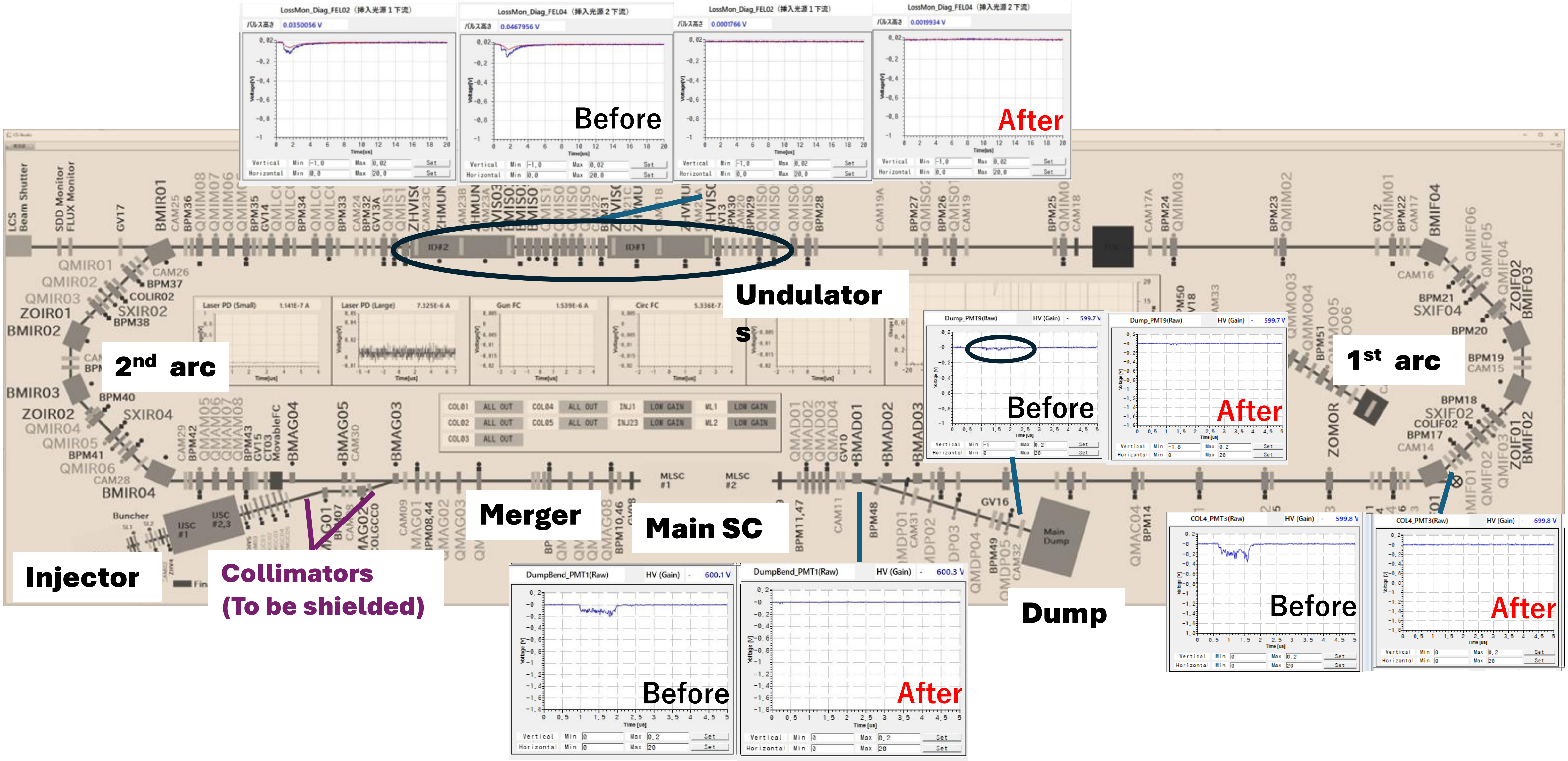
Machine learning tuning before the dump



Machine learning tuning of the collimators

Results

- Reduction of loss signals



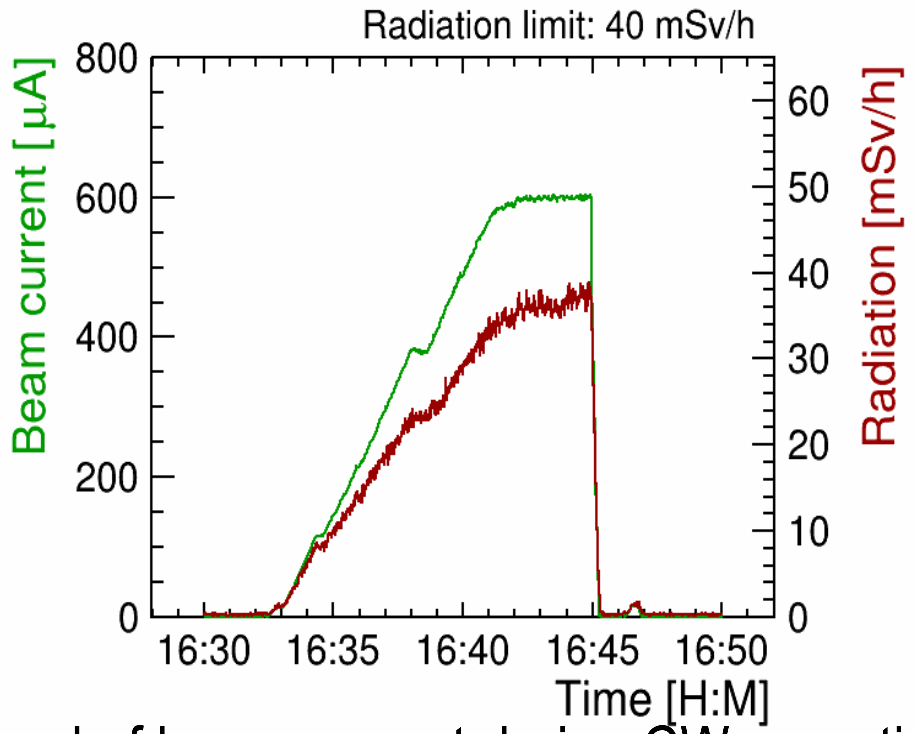
Results

- Obtained current for CW operation
  - Improved!

	Before ML	After ML
CW current [μA]	140	**600**

  - Target CW current: ~1 mA: not yet reached

- In this study, loss reduction before the dump was not enough
  - Needs thoroughly loss reduction
    - Even tiny loss signal is prohibited
    - Number of iteration
    - Detailed study of hyperparameters
    - Strategy of combining the loss monitor information
    - Application to more realistic situation



Trend of beam current during CW operation

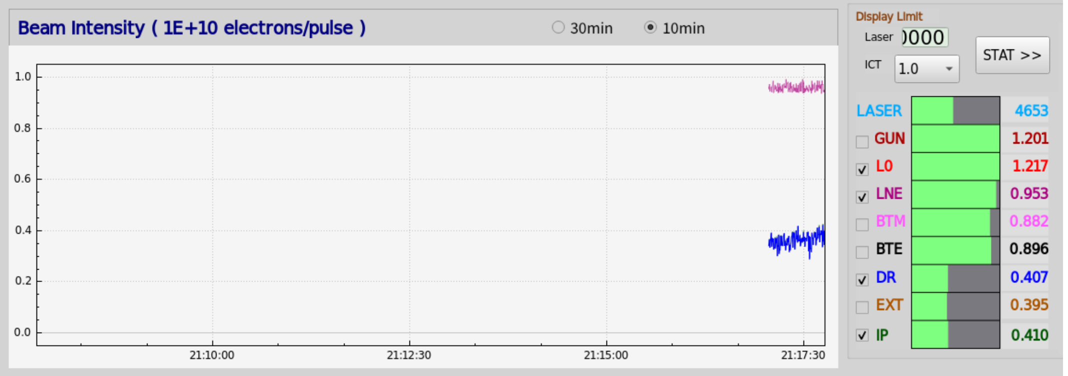
Summary and outlook

- Beam optimization using Machine Learning is going on at ATF/ATF2
  - FF tuning for nano-beam tuning: robust optimization
  - DR optimization for small emittance: new feature
    - Looks working for stable optimization: just the starting point
    - Need the knowledge for drastic improvement
- cERL: explore the possibility of auto-tuning for high current & low beam loss operation
  - Looks promising
  - Thorough beam loss reduction is important
  - Detailed study of hyper parameters
- This is for beam tuning feature
  - Flexible construction for any kinds of the targets
  - ML is suitable for other tasks
    - e.g.) Anomaly detection for machine protection
Tomography of phase space

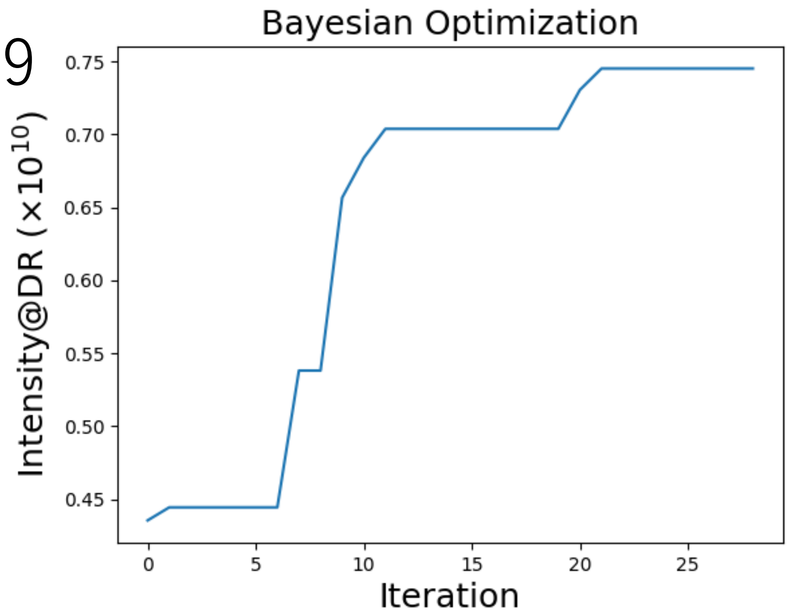
Backups

Linac tuning for high intensity @DR

- Optimize part of Linac components for high intensity @DR
- Example: Tune Linac phase of #1-#8 simultaneously
    - Before: just increase laser power
        - DR: only 4e9

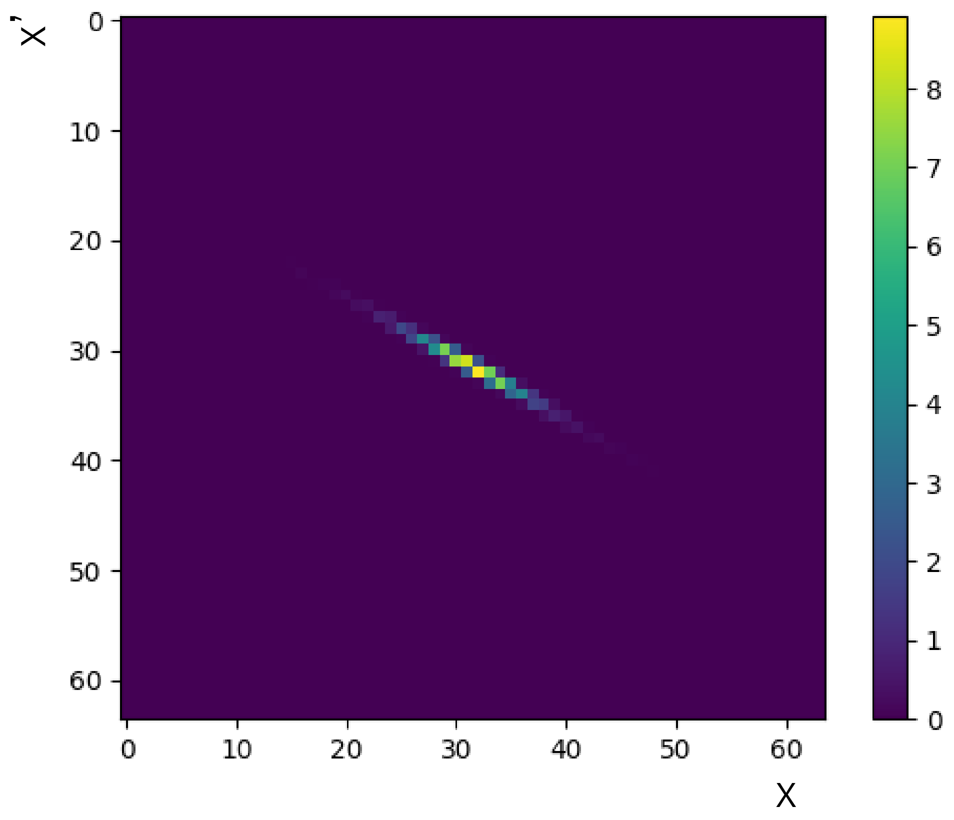


    - After: increase to 7.5e9
        - It takes ~9min. until optimize done
    - Tuning other linac parts by ML: 7.5e9 ⇒ >8.0e9

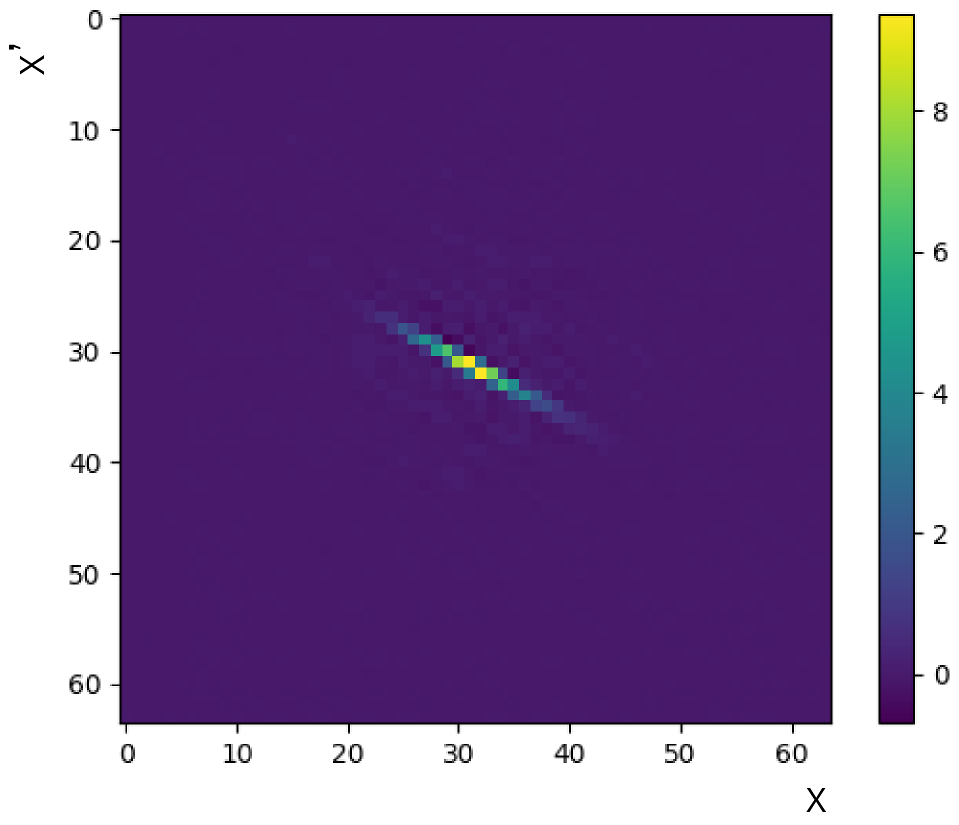


Preliminary: Tomography

- 図のx,y値は行列要素番号になってます。。
- z軸: macro particle数 / 100
- みため、よく似ているが、微妙に違う
    - Lossが大きいので性能が悪い
    - 現在、調査中
- 負値の出力への対処(network側でできると思う)



Answer



Prediction