cERL Operation

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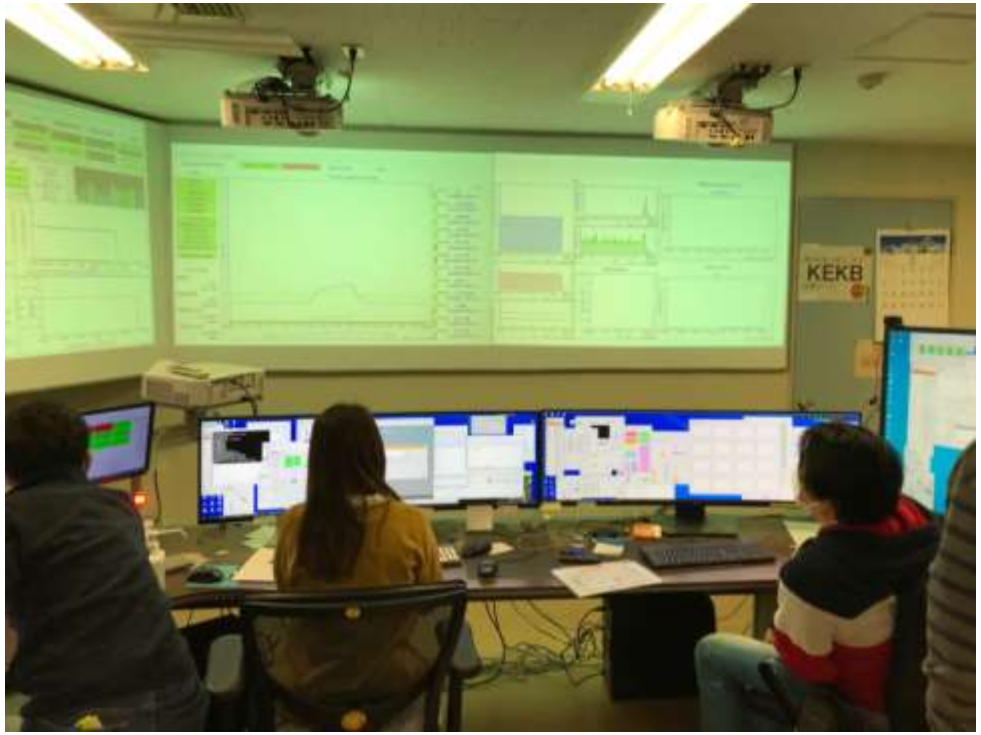
1. Control Room / Control System outline (just 1 page)

2. Beam Diagnostics and Machine Protection System (MPS) at cERL
   - YAG Screen Monitor
   - Beam Loss Monitor
   - Machine Mode and Fast MPS
   - Hardware trouble on 28/Feb/2022

3. Automation of beam tuning procedure
   - Bayesian Optimization

I. cERL Control System / Control Room

- Based on EPICS
- Linux Server on the backend, Windows Desktop, Projector for status display
- Control System Studio (CSS) for standard GUI and Alarm
- High-level Application : X Window+Python, Elegent/SAD, Jupyter Notebook, etc
- Archiver Appliance for history data
- PLC for standard equipment control (Yokogawa PLC with EPICS IOC)



Yokogawa PLC (Linux CPU + Ladder CPU)

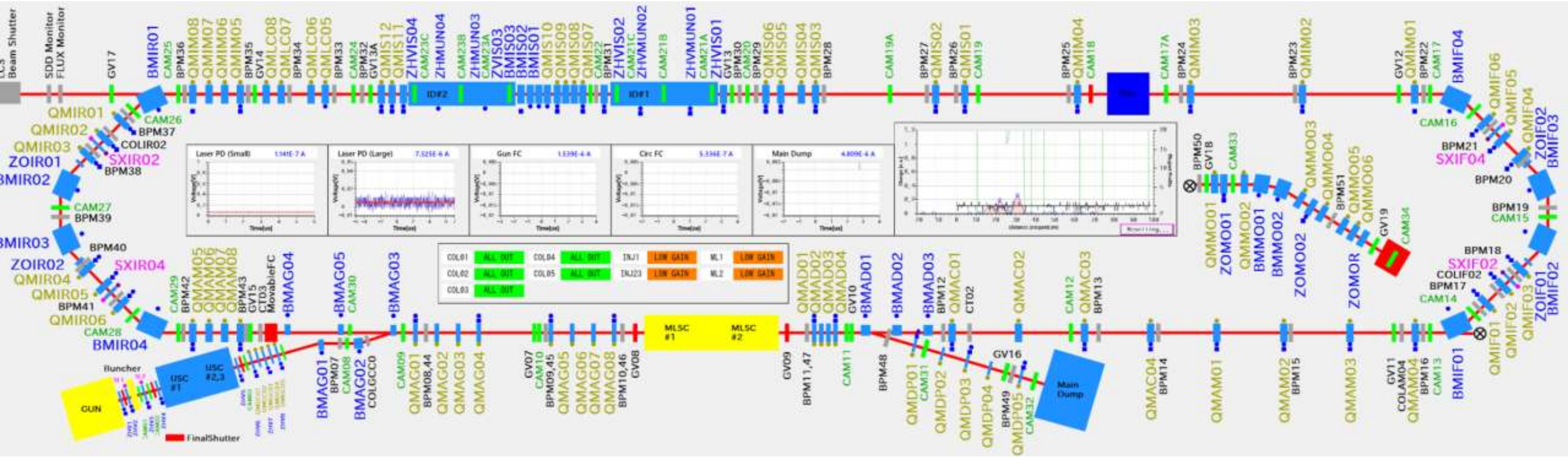
2. Beam Diagnostics in cERL

Circumference (from Gun to Main dump) : about 120m

Standard Beam Diagnostics

- 47 BPMs
- 40 Screen Monitors

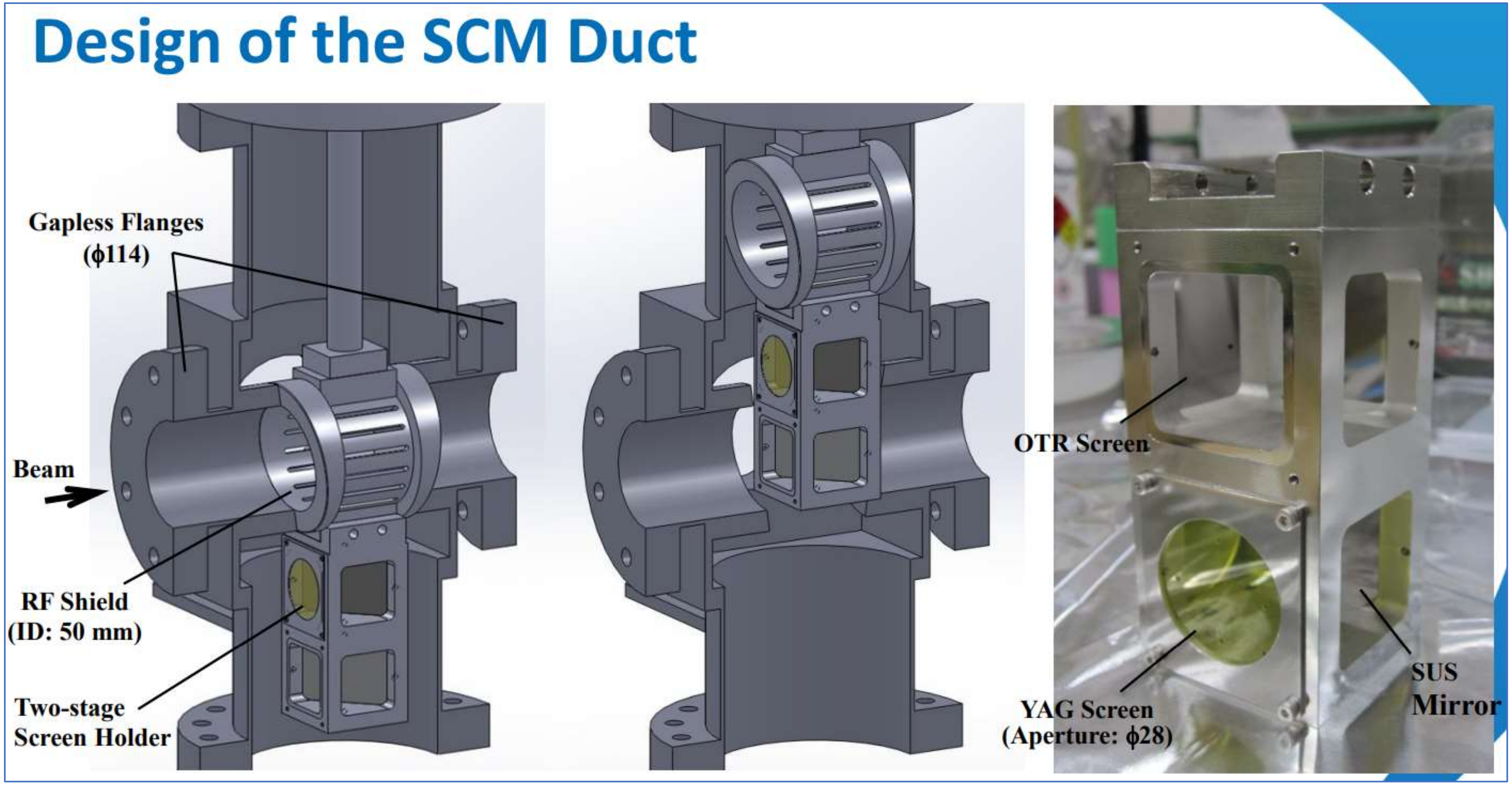
Please refer to the Sakai-san's talk last day.



Screen Monitor (SCM)

- YAG screen for low energy (or low charge) beam
- OTR target for high energy (or high charge) beam

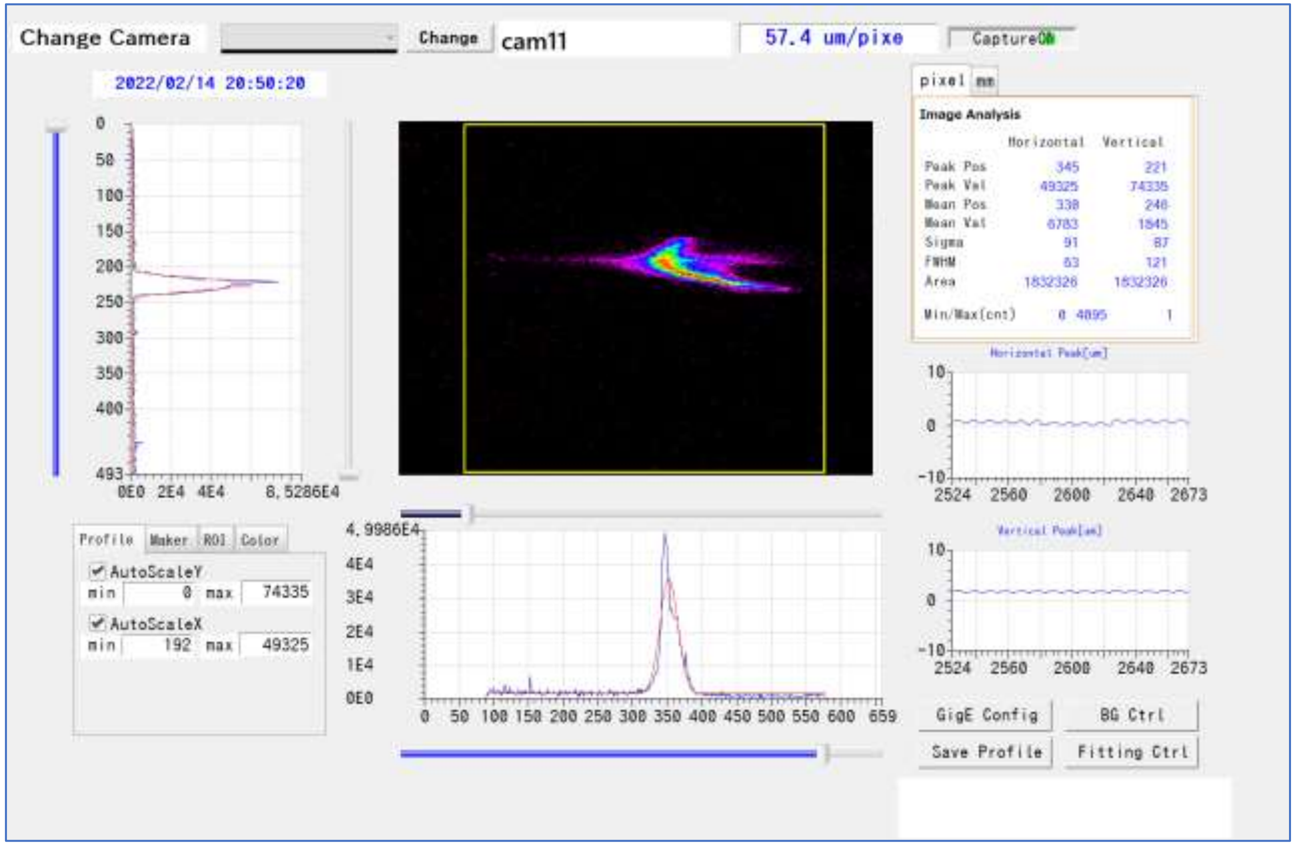
R. Takai, et.al. Proc. IBIC2014, MOCYB2
(※ based on JLab system)



Automation for diagnostics

SCM image GUI

- for manual beam tuning/analysis



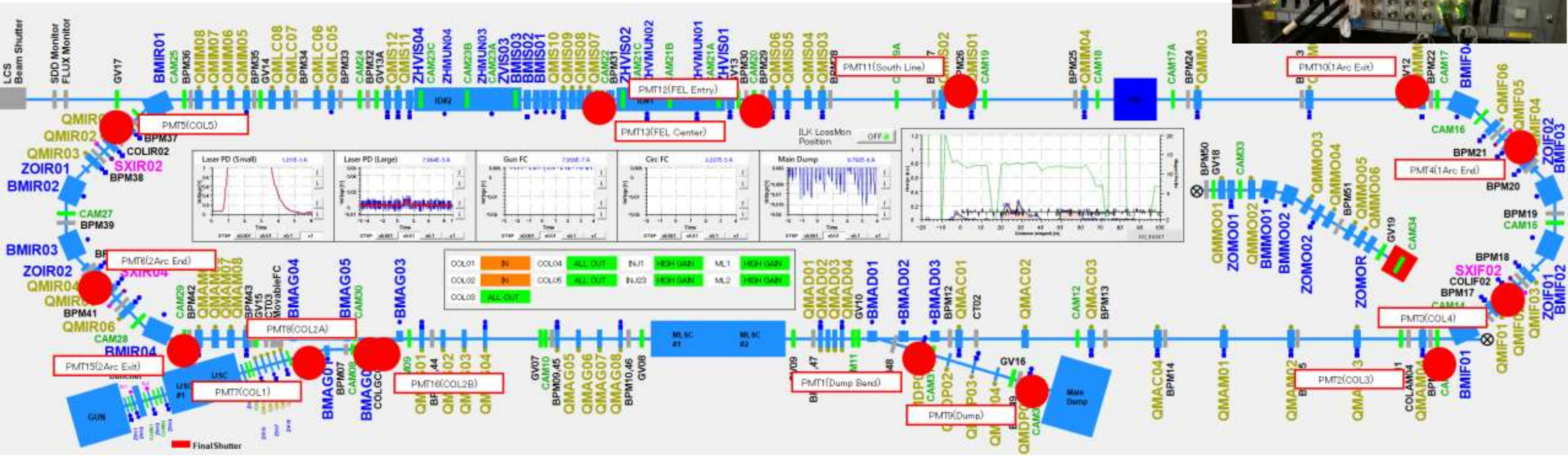
Automation : All Screen Capture

Note: SCM can be used ONLY in Burst mode.

Beam Loss Monitor

for Interlock : PMT + integration circuit → connected to fast interlock module

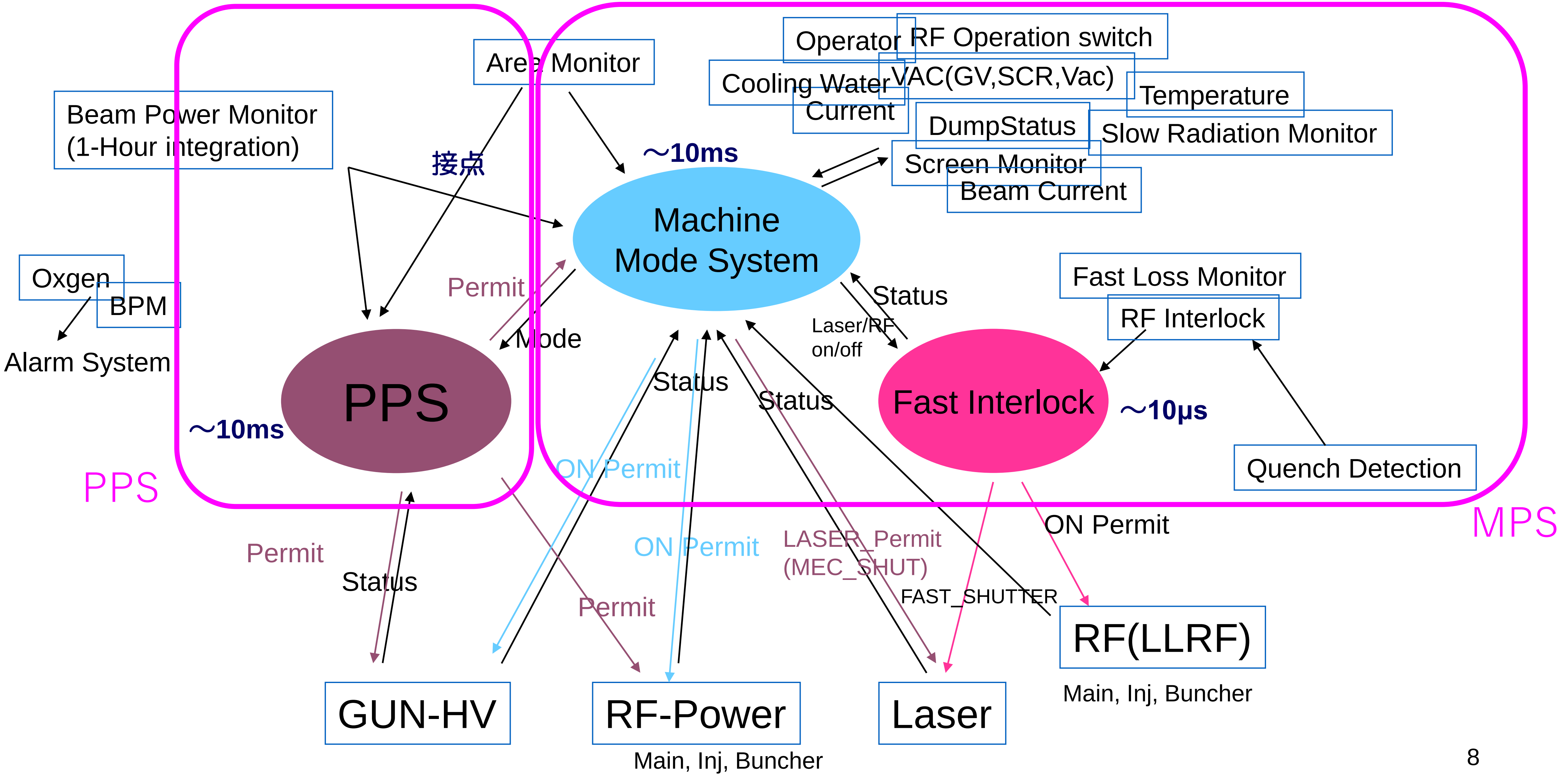
for Diagnostics : CsI(Tl) crystal + Photo Sensor Module



Loss Monitor Interlock system have been working fine for CW operation.

- There have been no incident until now.
- Loss monitor stopped the beam when the CW beam fluctuated

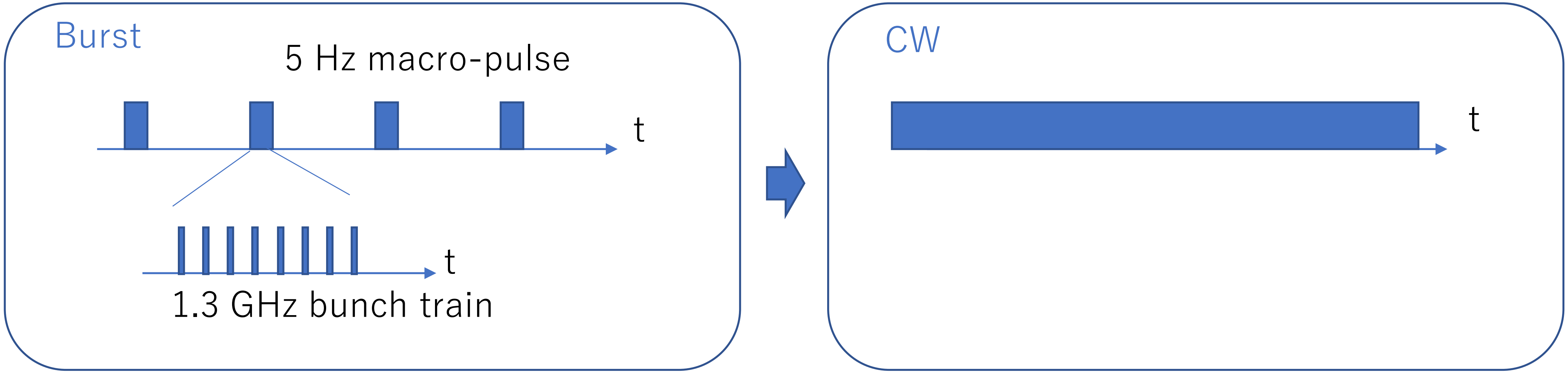
cERL Machine-Mode System (MMS)



Beam pattern and YAG screen monitor (SCM)

Beam pattern in cERL

- Burst (typically 100ns – 1us) macro-pulse mode, Rep-rate 1 – 5 Hz for SCM
- CW (pure continuous mode or long pulse of several ms)



We can open the laser shutter (Gate) when:

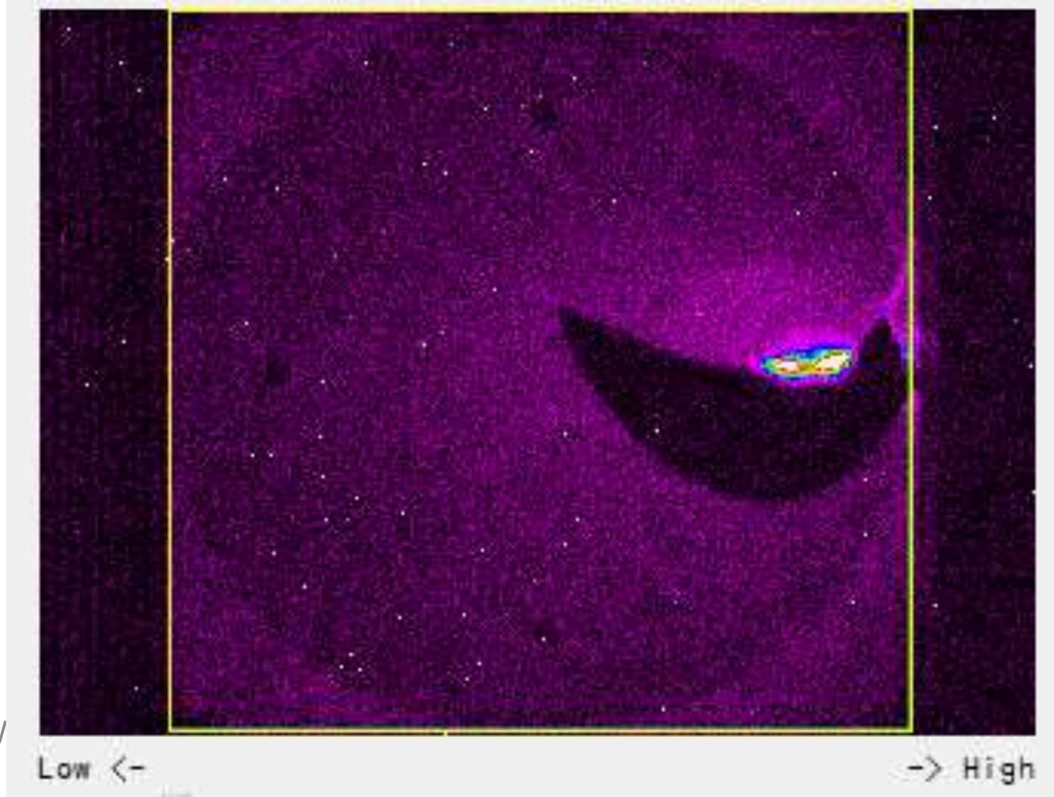
	BURST	CW
SCM OUT	permit	permit
SCM IN	permit	inhibit

It's quite simple.

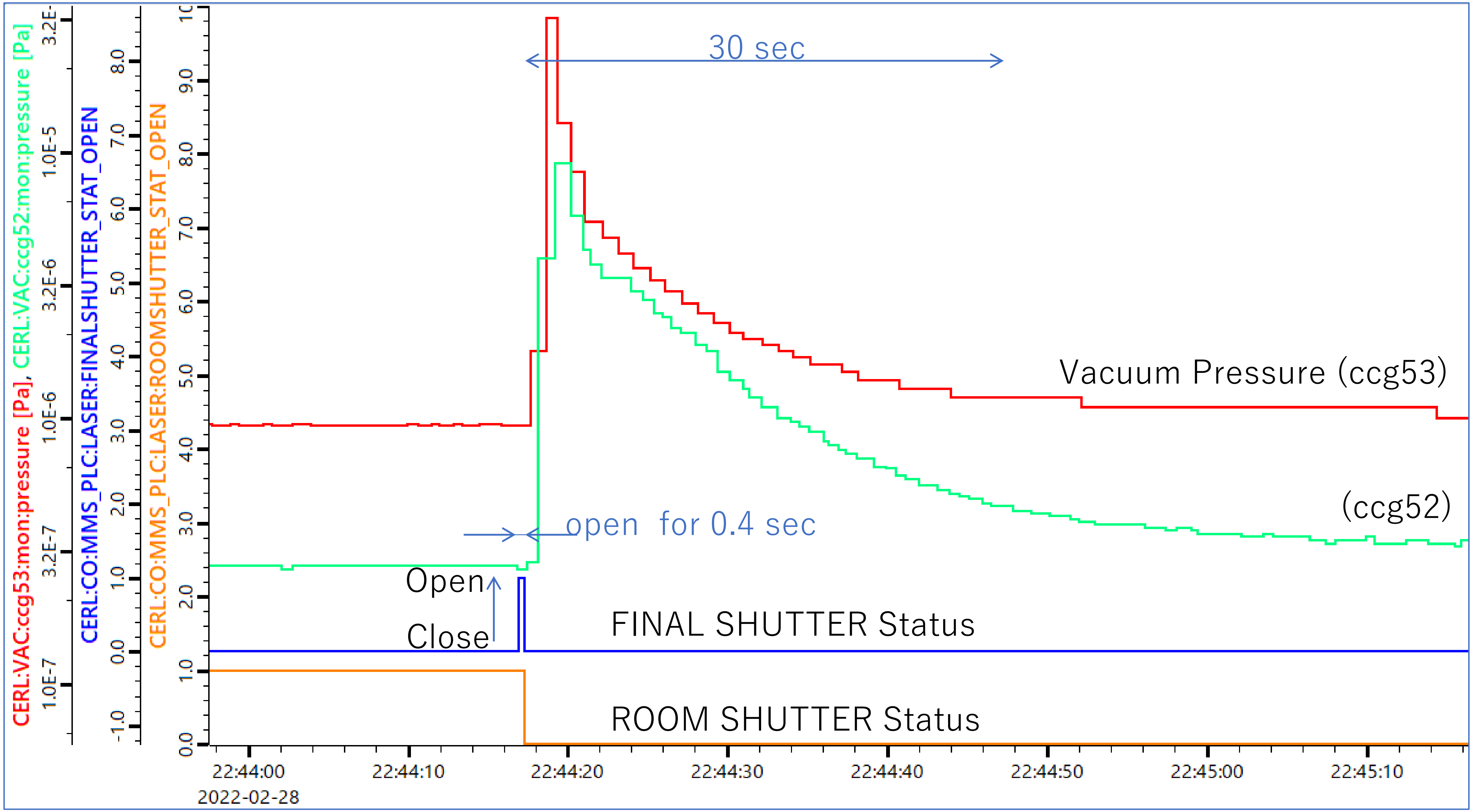
Failure on 28/Feb/2022

Event

- CW beam hit the YAG screen monitor.
  - Estimated beam power : 200 uA x 3.5 MeV = 700 W (at most)
- Observed: Vacuum pressure rise, Radiation increase inside concrete shield wall
  - Laser Shutter closed due to vacuum interlock
- No effect to the outside of the shield wall
- Later, we found a hole in YAG screen



Laser Shutter status and Vacuum Pressure



Failure on 28/Feb/2022

Immediate Action

- stopped the beam operation
- check no severe effect to SC cavity, Gun, and other components
- report to the radiation safety office

Cause

- Beam pattern from Burst to CW is O.K.
- There was a mistake in the transition operation from CW to Burst
- Defect in MMS: It did not monitor the real laser pattern.
- MMS thinks the laser is Burst, but in reality, the laser was operated in CW mode
- The operator opened the laser shutter, and the CW beam hit the YAG screen.

Historical Background

- In the beginning, an expert switched the laser pattern manually in a local laser room.
  - MMS cannot monitor the laser status at this time. Just believe the Human operation.
- A remote-controlled laser pattern switch system was introduced for the convenience of operation in 2019.
- MMS must monitor the laser status at this point. However, not implemented by mistake.

Lessons Learned

Countermeasure

- Now the Laser-pattern status is monitored by MMS all the time
- In case of "CW → Burst" transition, the Laser pattern follows MMS flag automatically
- MMS check inconsistency of each system (Laser pattern, Screen, Shutter, etc) and send permission signal to hardware.

Lessons Learned

- MPS (MMS)
  - When we add or update any equipment or systems, we must carefully check them.
  - Dry-run of MPS should be planned and performed by a third person
- Precise Timestamp is important
  - present time synchronization reliability between different system ～ 0.5 sec order
- We should allocate more resource (human/budget/time) on safety

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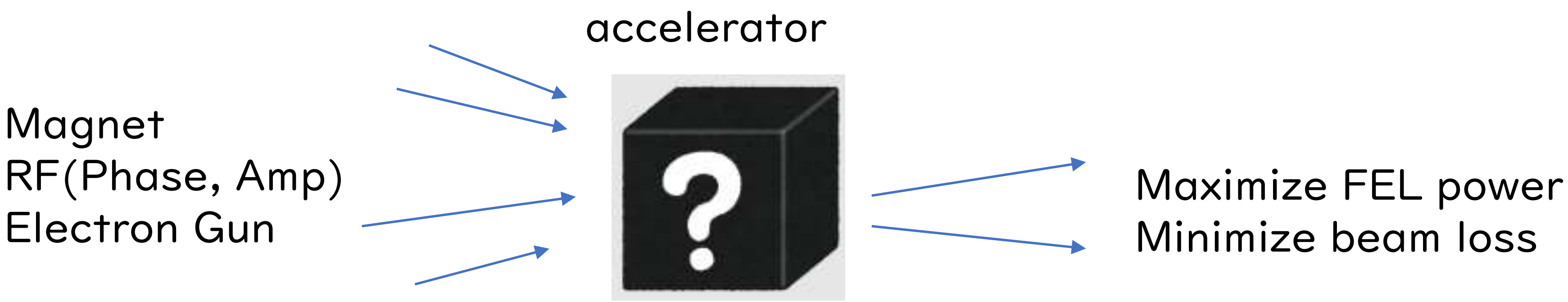
3. Automation of Beam Performance Tuning

Maximize (or minimize) some parameters【without any knowledge of model】

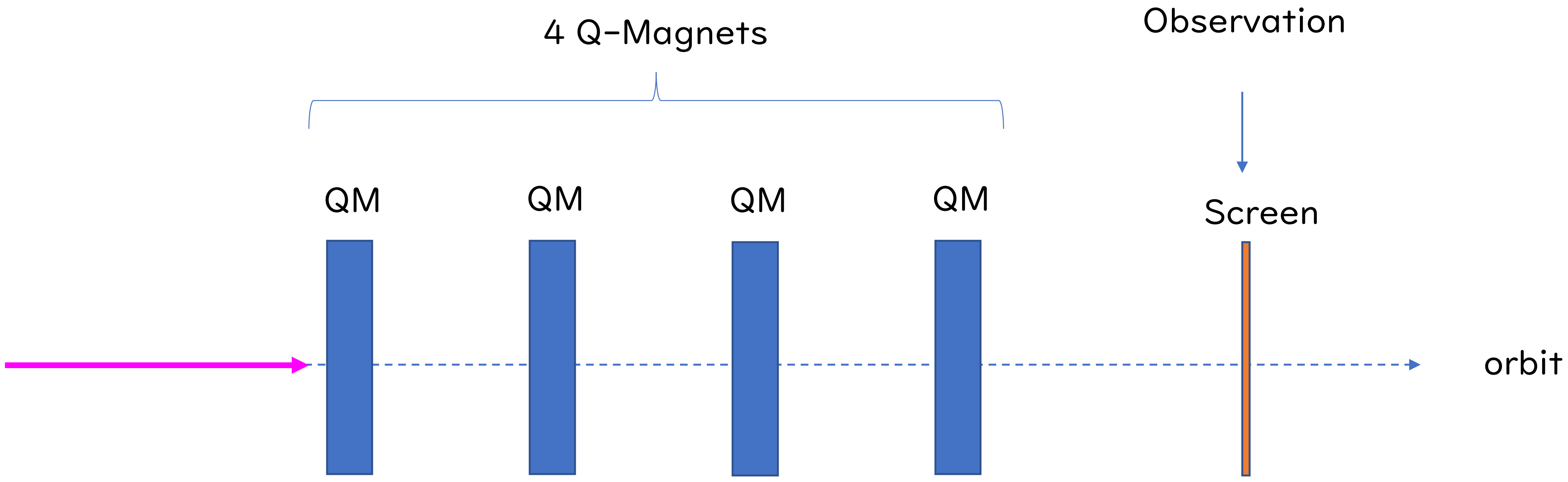


Black-Box Optimization or Design of experiments

We utilized a "Bayesian optimization (Gaussian Process)" for beam tuning.

Beam size tuning

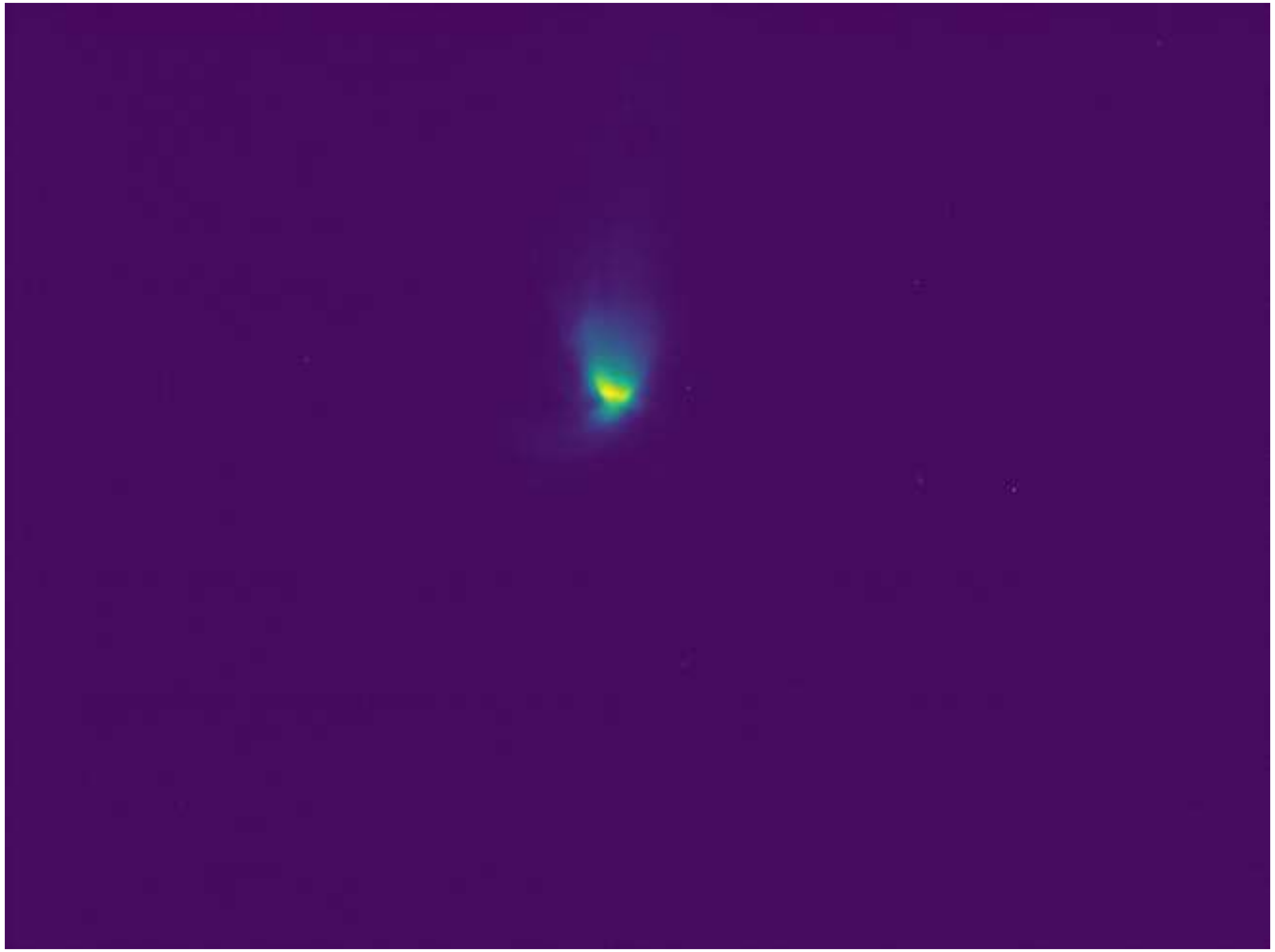
Minimize the beam size, higher intensity



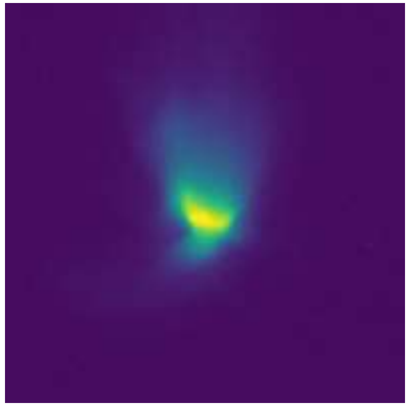
Next page: Movie during the beam tuning

Minimize the Beam Size

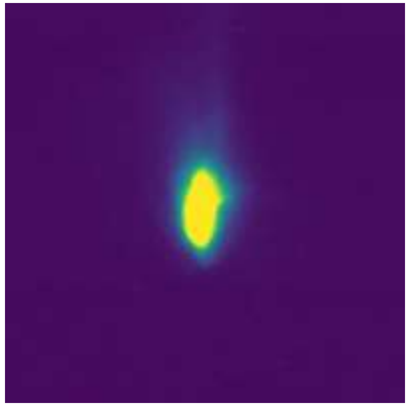
Automated tuning with GPyOpt



before



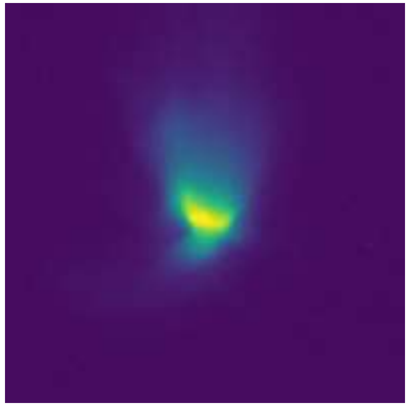
after



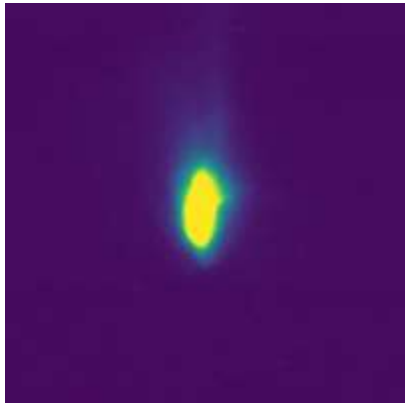
Yellow = Saturation
(Just for visibility)

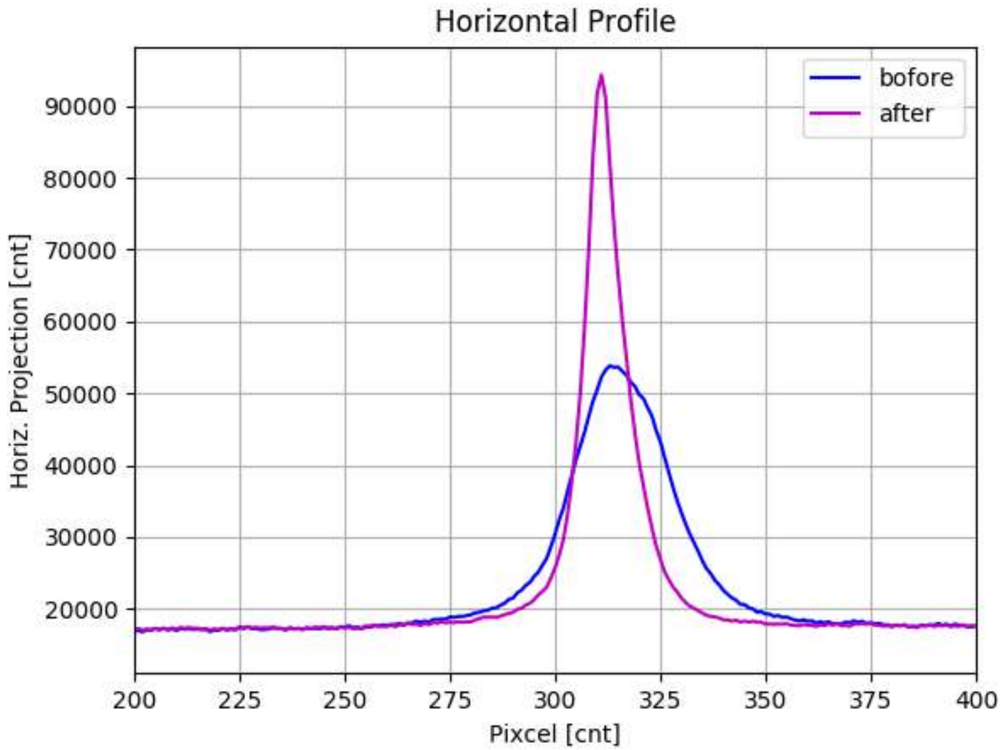
Beam profile tuning

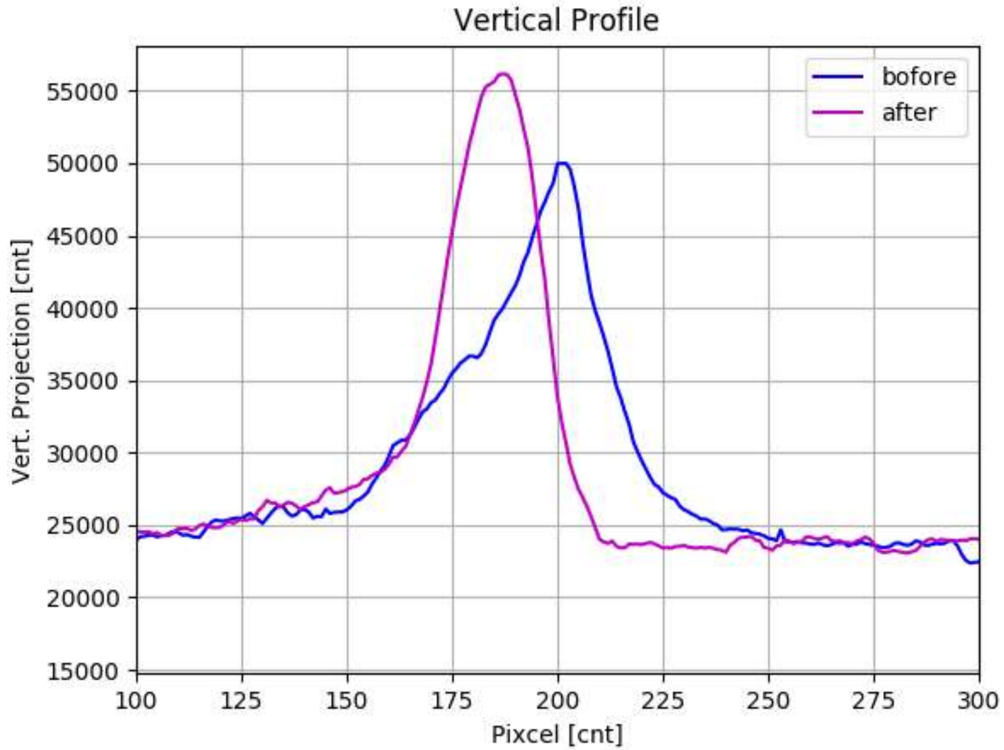
before



after

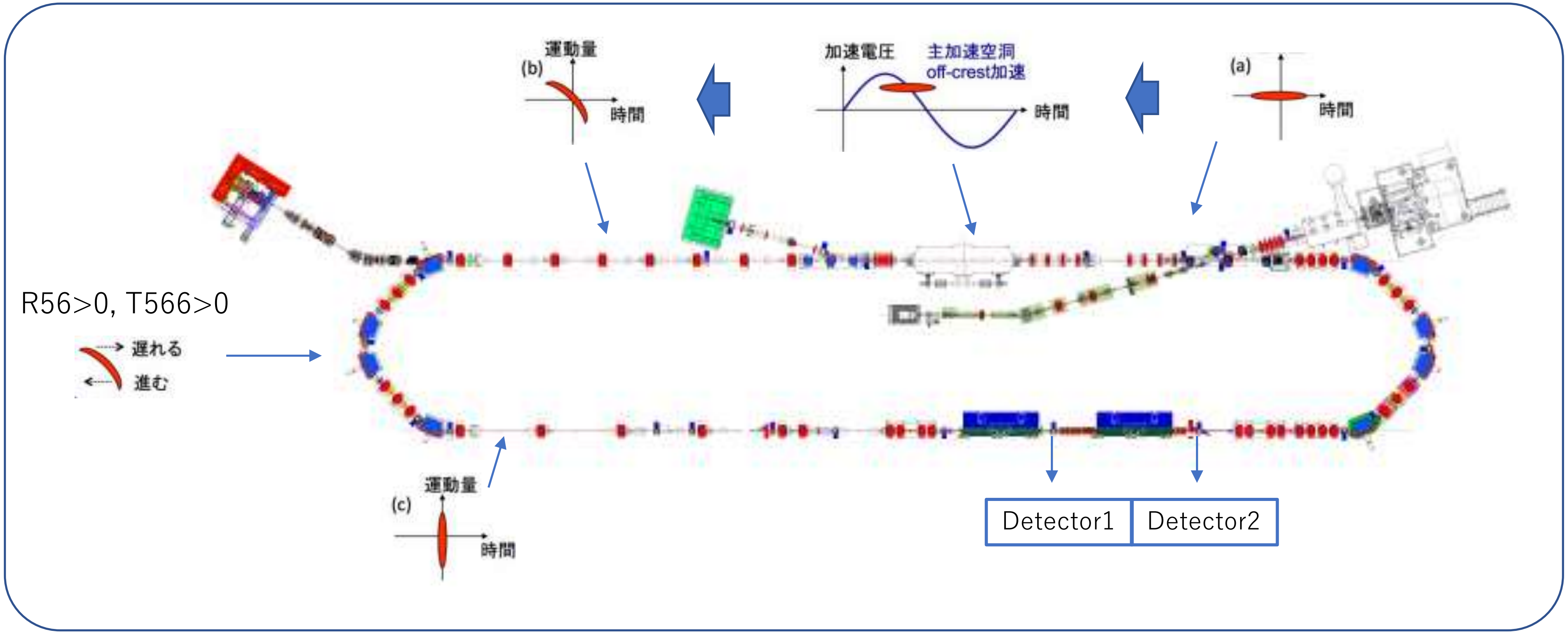






Target : Maximize FEL Power

Off-crest acceleration → energy chirp → R56, T566 for bunch compression



There are many parameters for beam tuning:
Space Charge(Transverse, Longitudinal) / Velocity Bunching / Magnetic field from other accelerator

Tuning "Recipe" with GP

Outline

- Maximize U1 power → U2 power

In each step

- Transverse tuning (Q-mag, steering mag)
- Longitudinal tuning with magnet (R56, T566, etc)
- RF (Main Linac/Injector Linac/Buncher)

Typically, optimization finished about 50 epoch

For detail, please refer to a paper:
Y. Honda, et.al.
"Construction and commissioning of mid-infrared self-amplified spontaneous emission free-electron laser at compact energy recovery linac"
Review of Scientific Instruments 92, 113101 (2021)
https://doi.org/10.1063/5.0072511

Operator Interface : Web browser

Jupyter Notebook + GPyOpt

- We have been created many panels after trial and error

組み合わせノブ

- 組合せノブ係数セットツール(テンプレートをコピーして使ってください) http://erlserv5.cerl.kek.jp:26005/tree/OP
- アーク部のR56調整
  - ARC1 Matching パネル　を使う。
  - http://erlserv5.cerl.kek.jp:26005/notebooks/OP/Combined_Knob
- アーク部6極
  - Six Matchingパネルを　使う。
  - http://erlserv5.cerl.kek.jp:26005/notebooks/OP/Combined_Knob
- 北直線部最後を使ってアーク中央を調整するやつ
  - NorthQ Matching パネル　を使う。
  - http://erlserv5.cerl.kek.jp:26005/notebooks/OP/Combined_Knob
- 北直線部最後を使ってアーク中央を調整するやつ
  - NorthQ Matching パネル　を使う。単純に個別の電磁石で。
  - http://erlserv5.cerl.kek.jp:26005/notebooks/OP/Combined_Knob
- U2ステアリング
  - QMIS07,10で位置と角度
  - http://erlserv5.cerl.kek.jp:26005/notebooks/OP/Combined_Knob
- U1マッチング

自動調整

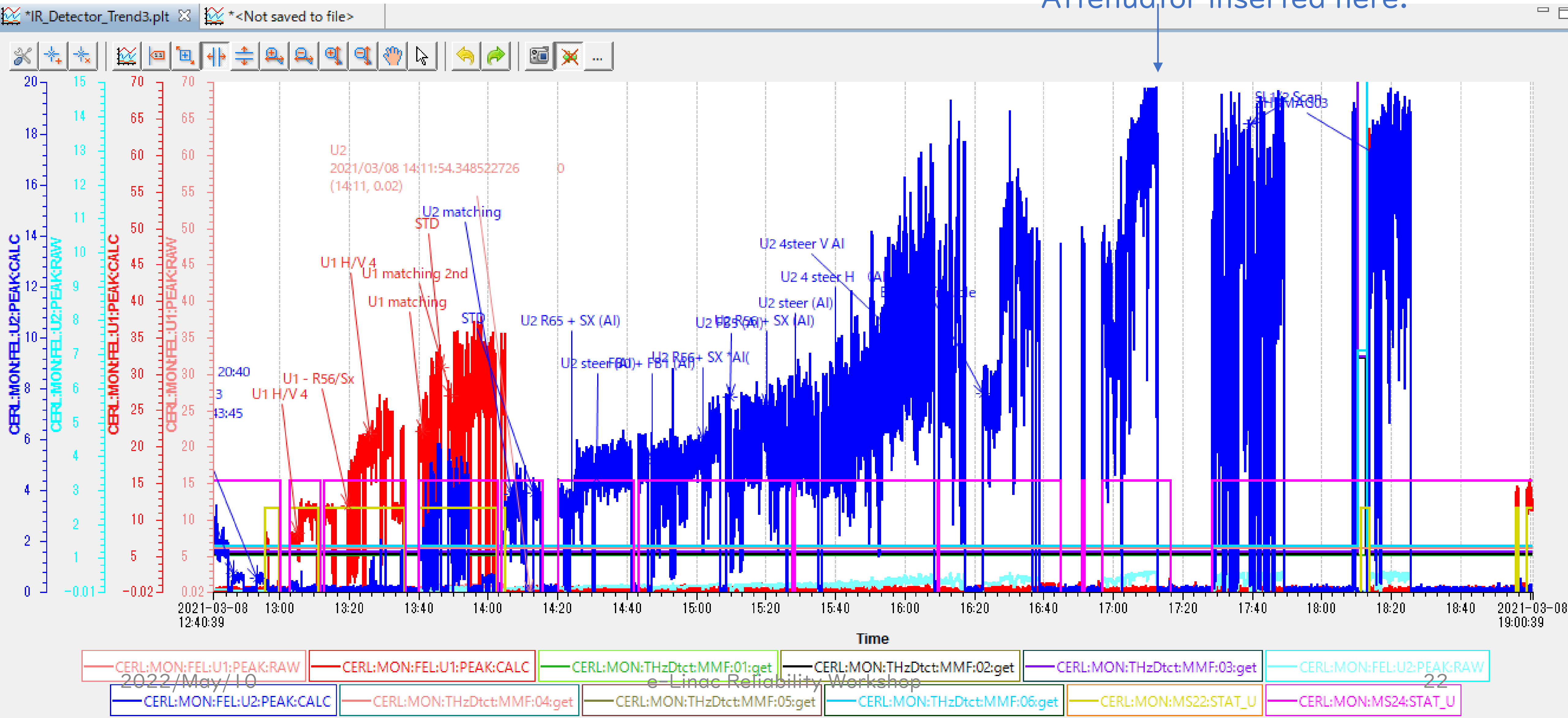
FELの調整に使うやつ

- Undulator MatchingのCombinedKnobの4パラメータを調整してU1のMCTを最大化するやつ
- Undulator MatchingのCombinedKnobの4パラメータを調整してU2のMCTを最大化するやつ
- アークR56とSXの3パラメータを調整してU1のMCTを最大化するやつ http://erlserv5.cerl.ke
- アークR56とSXの3パラメータを調整してU2のMCTを最大化するやつ http://erlserv5.cerl.ke
- アークR56とSXと分散漏れのパラメータを調整してU2のMCTを最大化するやつ http://erlserv
- バンチャーと入射器のLLRFの2パラメータを調整してU2のMCTを最大化するやつ http://erlse
- バンチャーと入射器のLLRFの4パラメータを調整してU2のMCTを最大化するやつ http://erlse
- ML1とML2のLLRFの4パラメータを調整してU2のMCTを最大化するやつ http://erlserv5.cerl.
- ML2のLLRFの2パラメータ(振幅と位相)を調整してU2のMCTを最大化するやつ http://erlserv
- U1上流のステアリング4つを調整してU1のMCTを最大化するやつ http://erlserv5.cerl.kek.jp
- U2上流のステアリング4つを調整してU2のMCTを最大化するやつ http://erlserv5.cerl.kek.jp
- U2上流の水平ステアリング4つを調整してU2のMCTを最大化するやつ http://erlserv5.cerl.ke
- U2上流の垂直ステアリング4つを調整してU2のMCTを最大化するやつ http://erlserv5.cerl.ke
- ソレノイドSL1とSL2を調整してU2のMCTを最大化するやつ http://erlserv5.cerl.kek.jp:260

FEL Tuning

Red：Undulator 1 Power, Blue：Undulator 2 Power

Detector Saturated.
Attenuator inserted here.



Summary

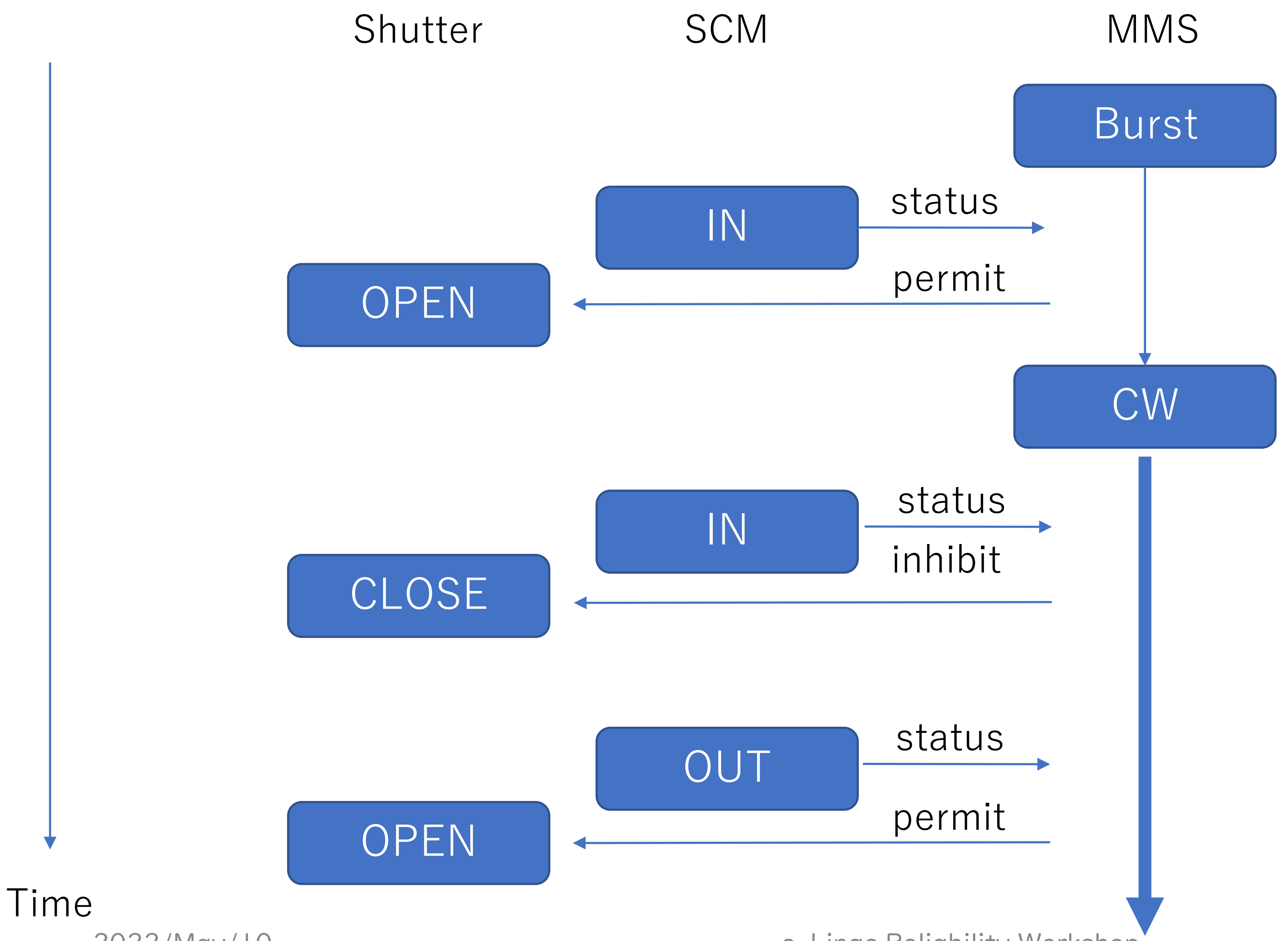
- MPS
  - Almost works fine, however, we experienced a trouble of breaking a YAG screen.
  - More reliable, robust system required.

- Bayesian Optimization with Gaussian Process is very powerful tool for various kind of beam tuning.
  - There are so many tools available now.
  - GPyOpt, PyTorch(Ax), GPyFlow, etc
  - It is important to use good evaluation function.

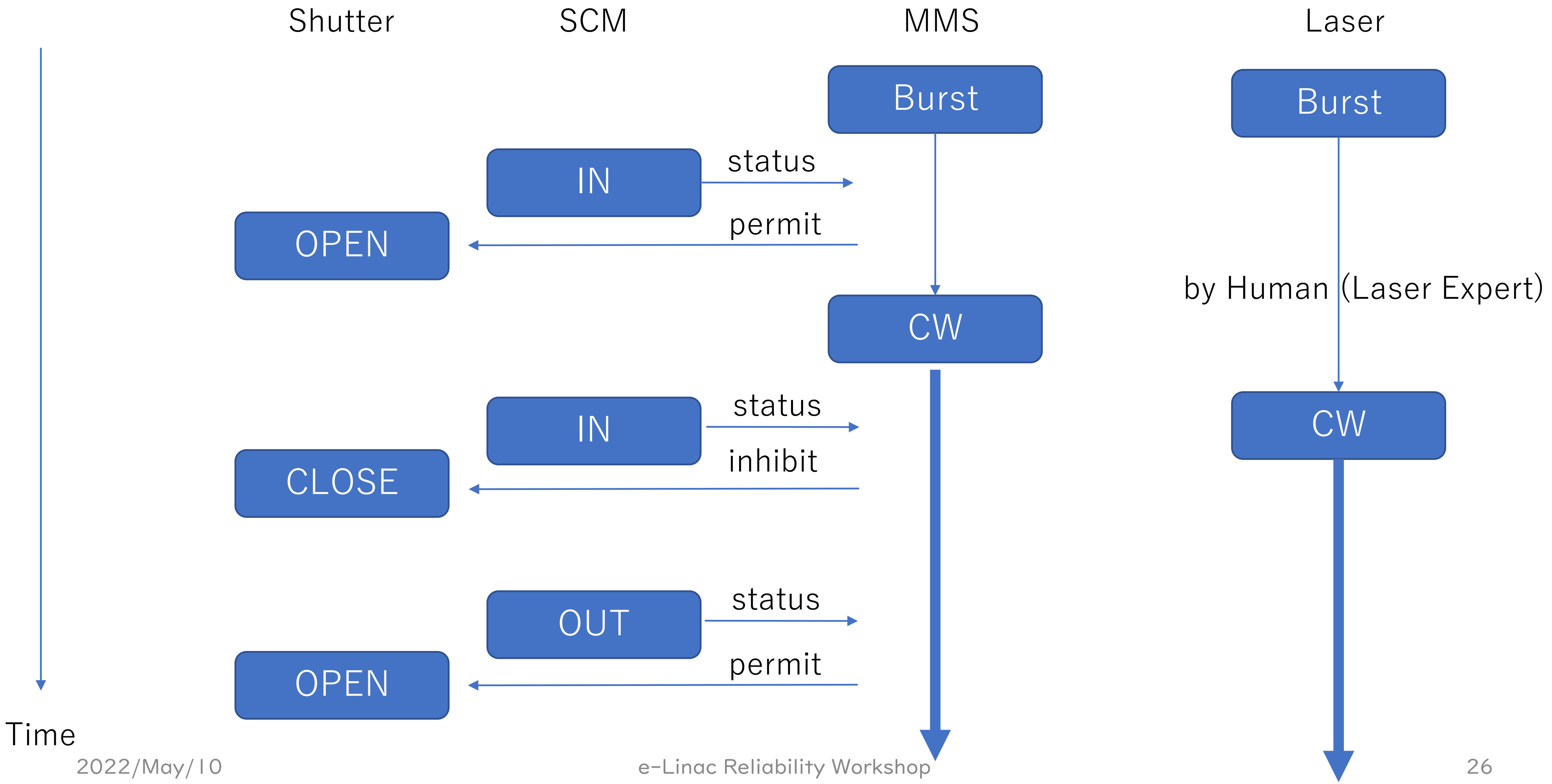
- Future Topics
  - Need more discussion with expert : "Data Science" "Machine Learning"
  - Higher dimension (more parameter space)
  - A safe Bayesian optimization (SafeOpt) is also an important topics for accelerator tuning. (Bayesian optimization with safety constraints)

backup slides

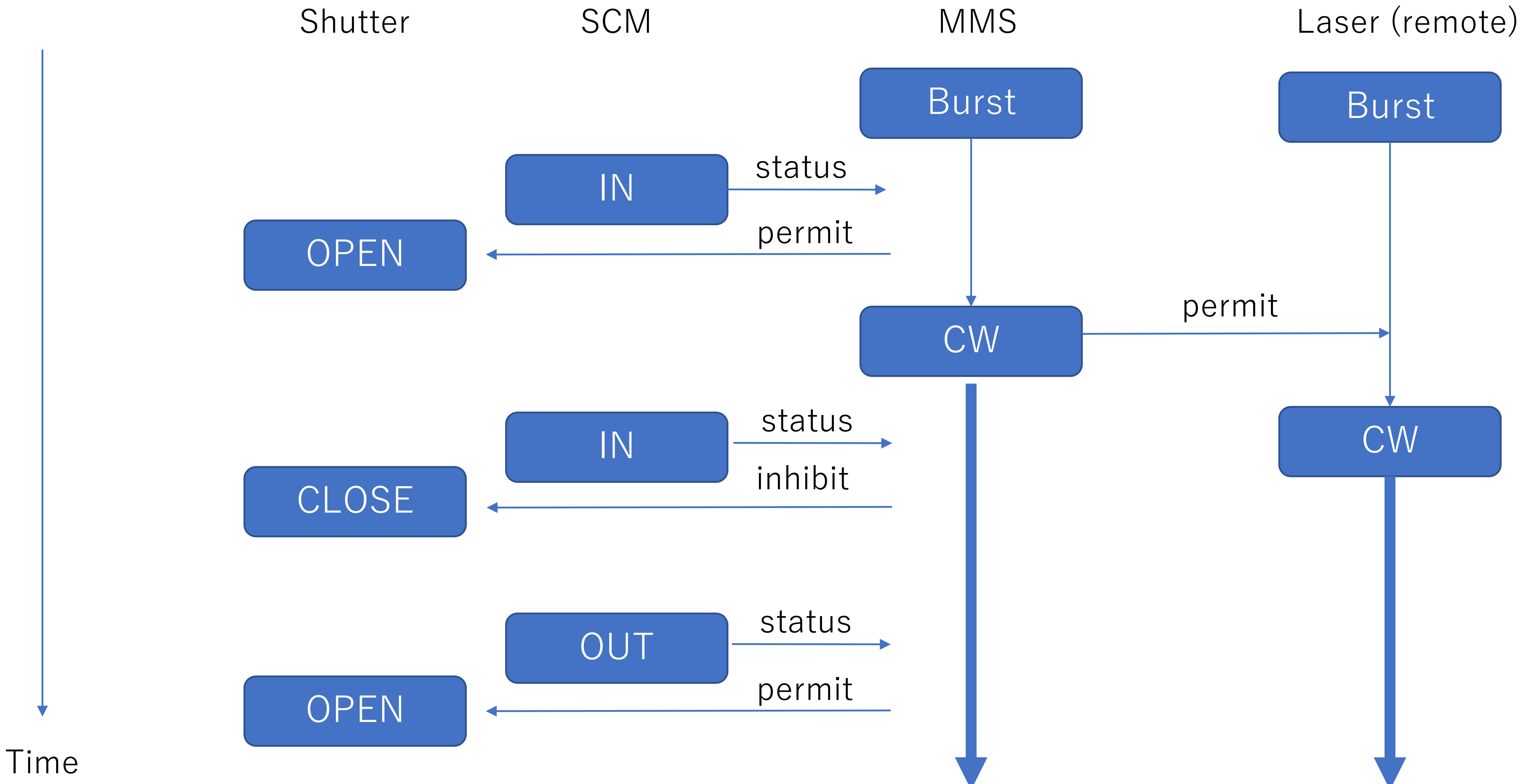
MMS monitors HW status and handle inhibit/permit.
Open/Close or In/Out operation is done by operator.



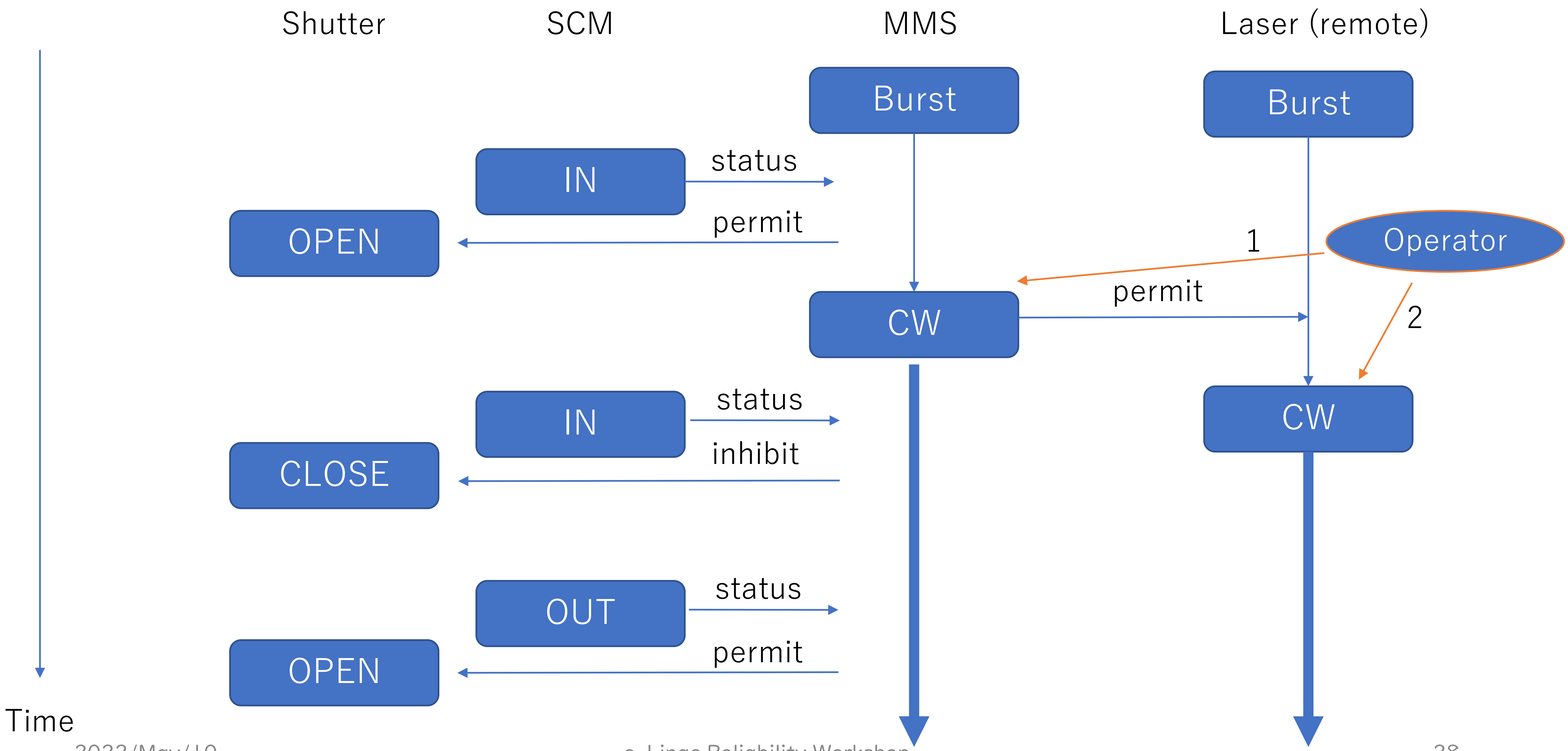
At the beginning stage, laser pattern can only change by an expert.
We call the expert after we changed the MMS flag.



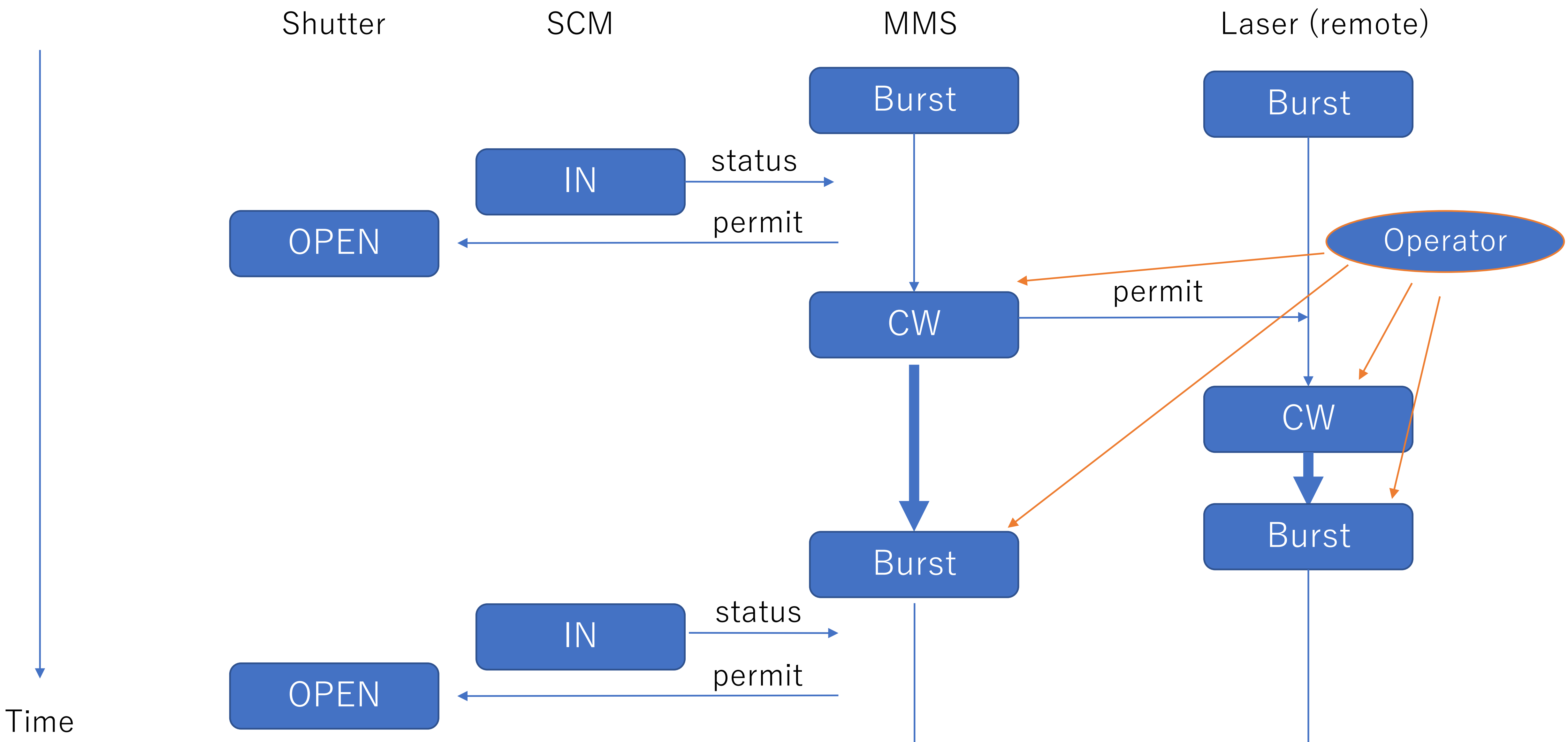
Remote switching system was introduced in 2019.
The system monitor the MMS flag.



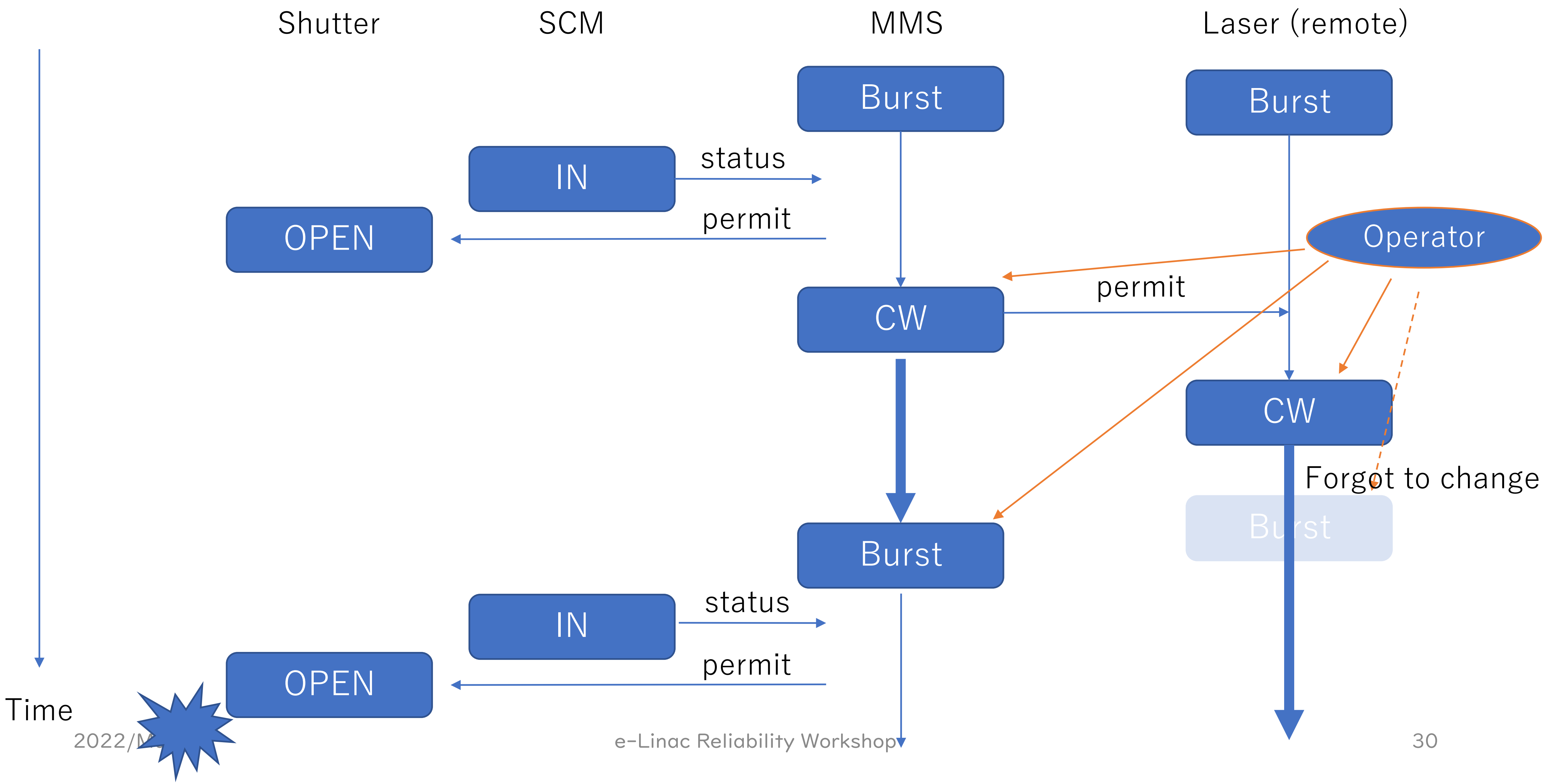
In this case, the operator changed MMS flag, then switch the laser to CW.



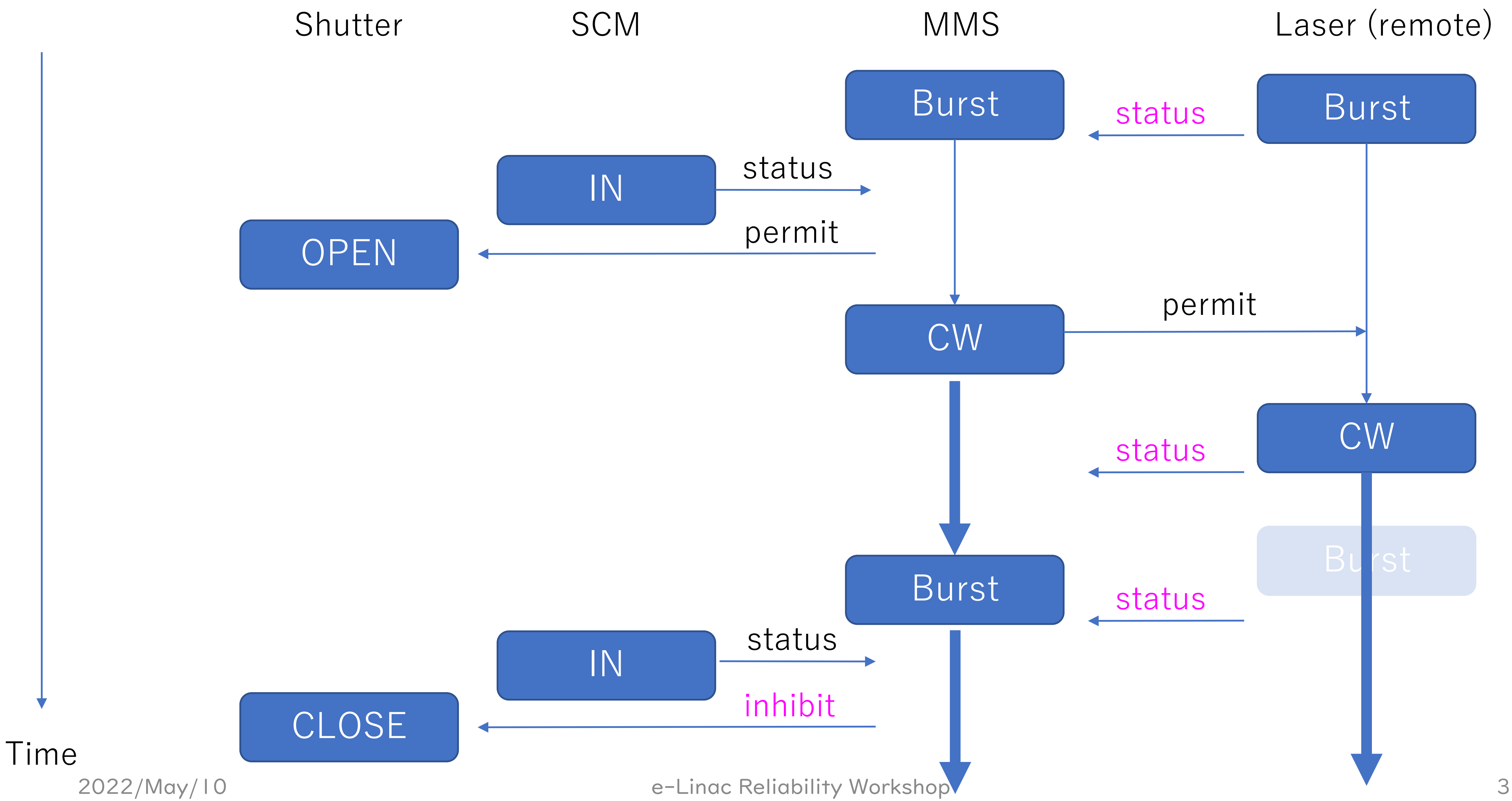
When we go back from CW to Burst, the operator must change BOTH the laser and MMS.



What happened on 28/Feb.
Note that this is NOT the mistake of the operator.



Defect of MMS. MMS must always monitor the status of the laser. (which did not exist at the Human-Switching era)



Also, we introduced an automatic change sequence.