Compact ERL (cERL), Stable 1 mA Operation with a Small Beam Emittance at KEK

9:55-10:30, September 16, 2019
Workshop on Energy Recovery Linacs (ERL2019)
Helmholtz-Zentrum Berlin

Tsukasa Miyajima
KEK, High Energy Accelerator Research Organization
On behalf of cERL team

大学共同利用機関法人
高エネルギー加速器研究機構 (KEK)
加速器研究施設
Accelerator Laboratory

Outline

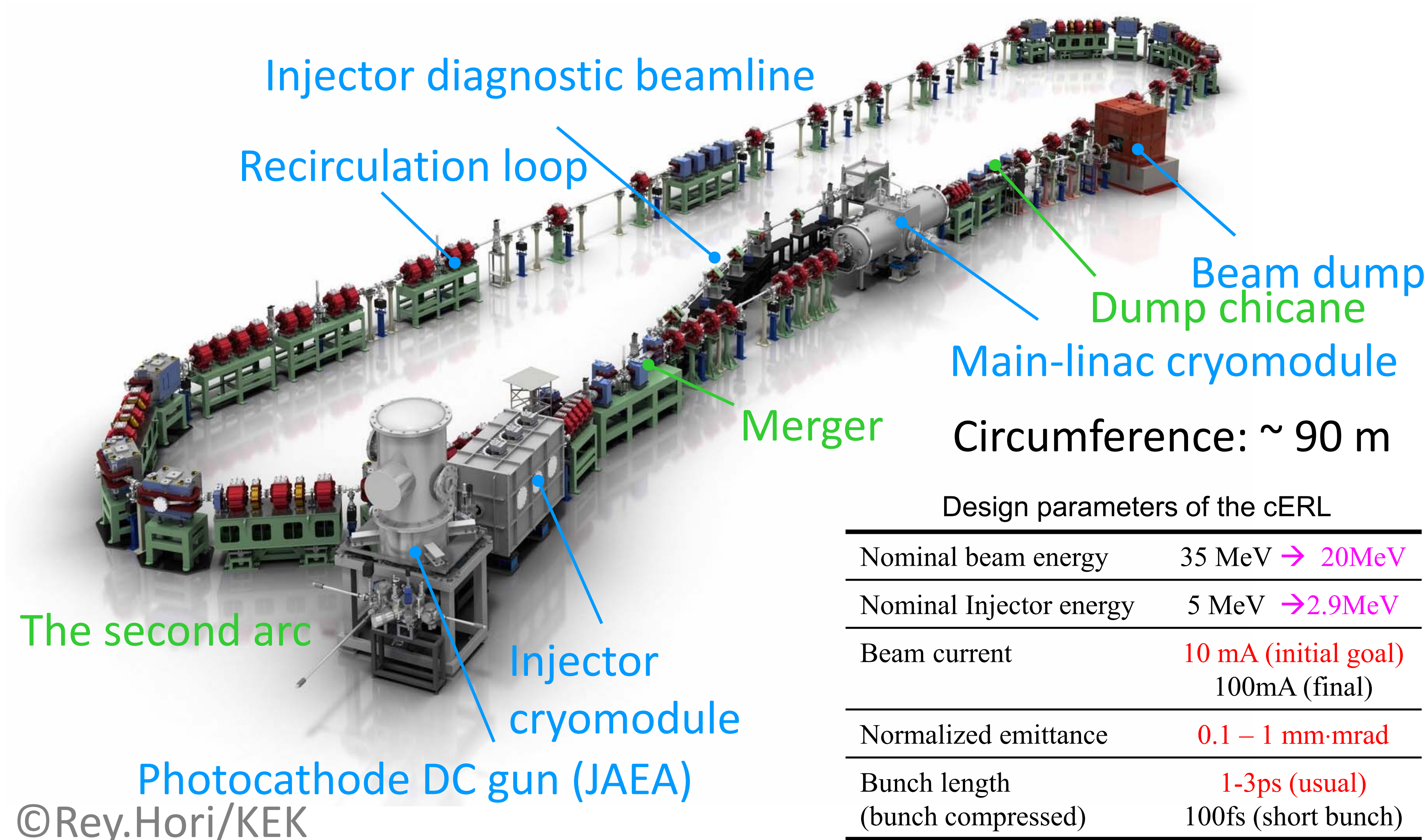
- Current status of compact ERL (cERL) in KEK
  - History and Change the target from academia to industry of cERL
  - Now, cERL is not “legacy”.
- CW 1 mA operation in cERL
  - How to stabilize CW operation?
  - How to control beam loss?
  - How about is the beam quality?
- Summary

ERL19 presentations about cERL operation

- T. Miyajima, “Compact ERL(cERL), stable 1 mA operation with a small beam emittance at KEK” (Mon)
- O. Tanaka, “Beam Halo” (Tue)
- H. Sakai, “KEK ERL SRF Operation Experience” (Tue)
- F. Qiu, “Characterization of Michrophinics in the cERL main linac superconducting cavities” (Tue)
- M. Shimada, “”High-efficiency broadband THz emission via diffraction-radiation cavity” (Wed)
- E. Kako, “Degradation and Recovery of Cavity performance in Compact-ERL injector cryomodule at KEK” (Thu)

Compact ERL at KEK

- Test accelerator to demonstrate ERL technology



Circumference: ~ 90 m

Design parameters of the cERL

Nominal beam energy	35 MeV → 20MeV
Nominal Injector energy	5 MeV →2.9MeV
Beam current	10 mA (initial goal) 100mA (final)
Normalized emittance	0.1 – 1 mm·mrad
Bunch length (bunch compressed)	1-3ps (usual) 100fs (short bunch)

Operation history of cERL

2013 Jan. – Jun.	Jul. – Dec.	2014 Jan. – Jun.	Jul. – Dec.	2015 Jan. – Jun.	Jul. – Dec.	2016 Jan. – Jun.	Jul. – Dec.

1 μA

Injector operation without recirculation loop (Apr. - Jun.), maximum 1 μA
Generation and acceleration of electron beam to 5.6 MeV
Achieved normalized emittance: < 0.8 mm mrad with 7.7 pC

10 μA

ERL operation (Dec. – Mar.), maximum 10 μA
Acceleration of electron beam to 19.4 MeV
We succeeded in energy recovery operation.

ERL operation (May – Jul.), maximum 10 μA
Beam optics measurement
Achieved normalized emittance: 5.8 mm mrad with 7.7 pC

100 μA

LCS-X-ray experiment (Jan. – Mar.), max. 100 μA
Optics tuning for LCS experiment
Generation of LCS-X-ray

Low emittance tuning (May – Jun.), max. 100 μA
Compensation of space charge effect
LCS-X-ray experiment

Maximum CW current

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Generation of LCS-X-ray

Low emittance tuning (May – Jun.), max. 100 μA
Compensation of space charge effect
LCS-X-ray experiment

1 mA

High current operation (Feb. – Mar.), max. 1 mA
We achieved 0.9 mA energy recovery operation.
Bunch length compression < 100 fs, experiment of coherent THz radiation
Low emittance tuning, Gun voltage: 390 kV ⇒ 450 kV

Maximum CW current

History and Change the target from academia to industry of cERL

2013-2015 The beam commissioning started in 2013 for future 3 GeV ERL light source and achieve CW 1 mA under energy recovery operation

2016 The future light source was shifted to the high-performance storage ring. On the other hand, KEK directorates kept the importance of the R&D for industrial application based on ERL technologies.

http://www.kek.jp/ja/NewsRoom/Release/20160802141100/

2017 ERL project Office was closed in KEK… However, "Utilization Promotion Team based on Superconductive Accelerator (SRF-application team)" was kept in KEK.

2018 Change the team leader of "SRF application team" from Prof. Kawata to Prof. Hiroshi Sakai.

Restart the beam operation by using cERL for SRF application. (2018.Mar. & Jun. (1mA))

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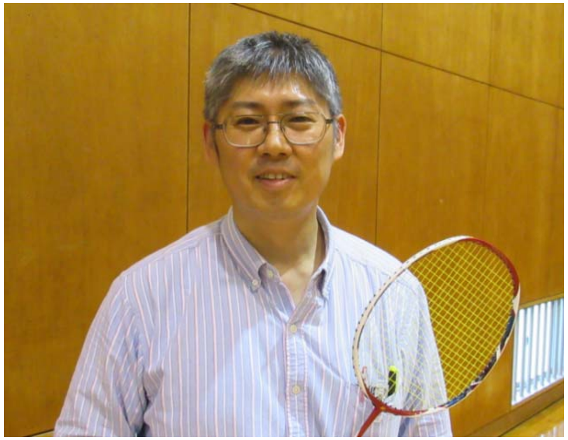
Hiroshi KAWATA (KEK)



Hiroshi SAKAI (KEK)

cERL: for future light source ⇨ for industrial applications

Industrial Application of ERL technology

EUV-FEL for Lithography, High intense LCS sources, THz source, RI factory and so on

- High average CW current electron beam
- High quality of the electron beam with high bunch charge:
  - Small Emittance, short pulses, and so on

These two topics are still important for industrial applications.

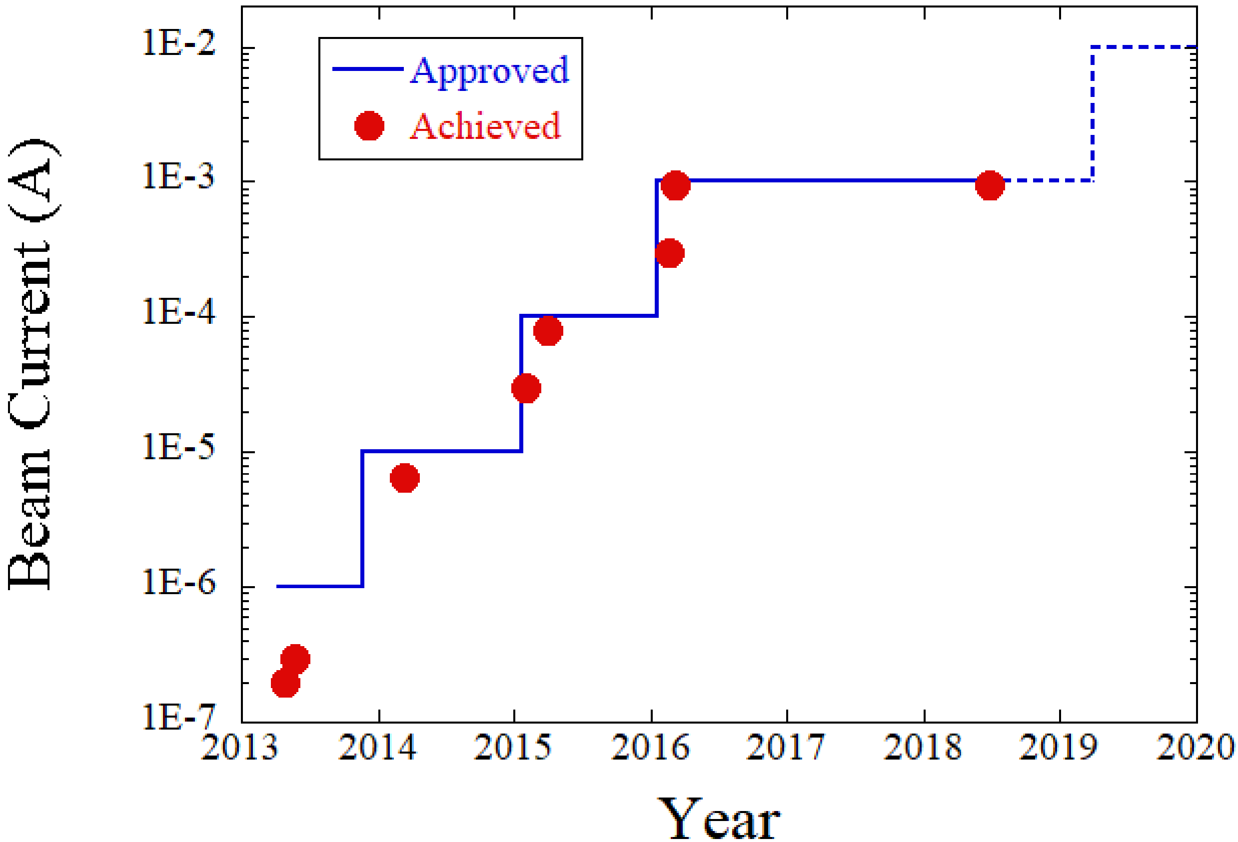
- We restarted beam operation of cERL from 2017.
  - March 2017: High bunch charge operation (max. 40 pC/bunch) to develop beam handling method toward high average current FEL.
  - March 2018: High bunch charge operation (max. 60 pC/bunch)
  - June 2018: CW 1 mA operation to reduce un-wanted beam loss and halo.

    Resonant Coherent Diffraction Radiation (RCDR), to generate intence THz.

Target of CW current for industrial application: CW 10 mA
So far, we have achieved stable CW 1 mA operation, and the next target is to demonstrate CW 10 mA operation.

History of achieved CW beam current

- In the cERL, the radiation shield restricts beam loss.
- To increase CW beam current, the mitigation of beam loss is very important.
- Oure strategy: we start beam operation with low CW current to understand and to control beam loss.



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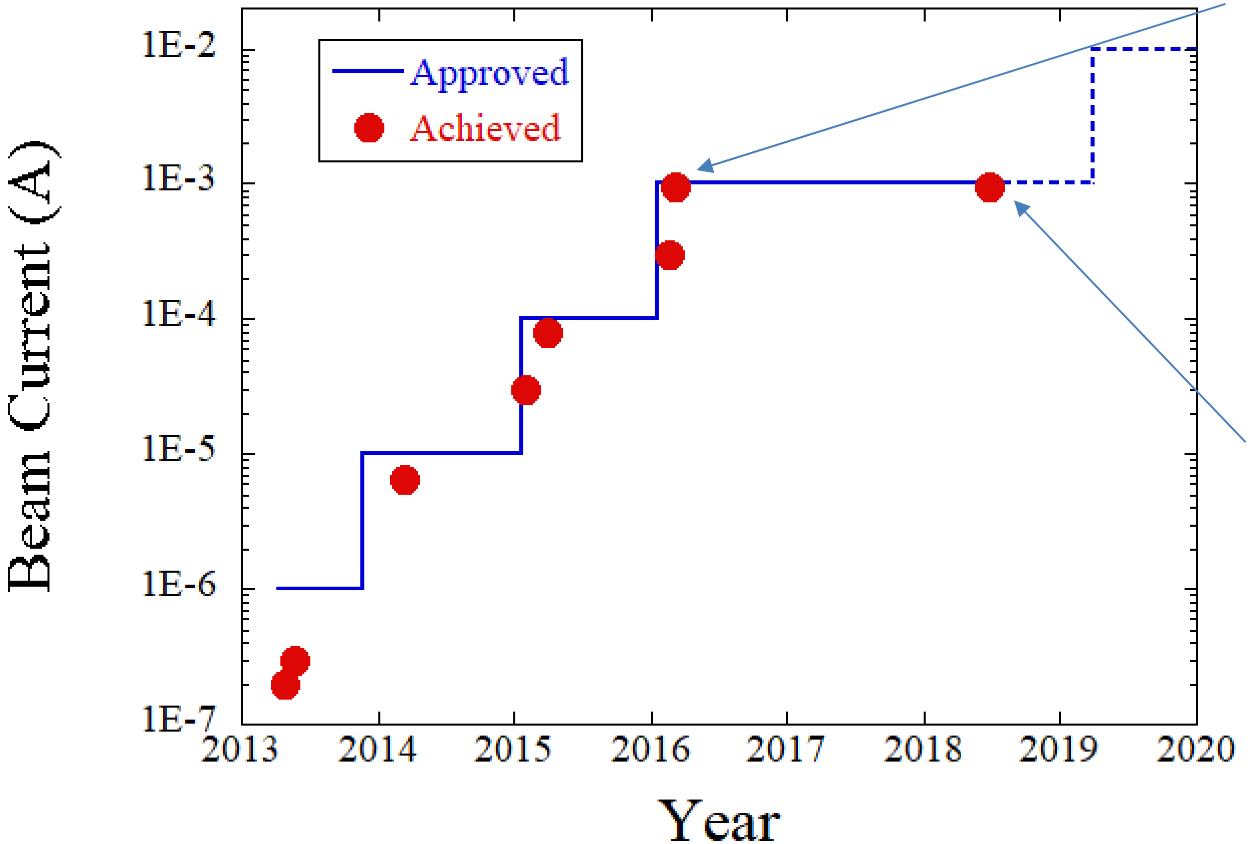


<u>March 2016</u>
Bunch charge: 5.5 pC
Gun: 390 kV
Injector: 2.9 MeV
Loop: 20 MeV

- How to stabilize CW operation?

<u>June 2018</u>
Bunch charge: 0.77 pC
Gun: 500 kV
Injector: 3.0 MeV
Loop: 17.6 MeV

- Can we reproduce stable CW operation?
- How about is the effect of decreasing loop energy?

Problems of previous CW operation

Previous CW operation in 2015

- CW operation: Average current 0.075 mA（charge: 0.46 pC, 162.5 MHz）

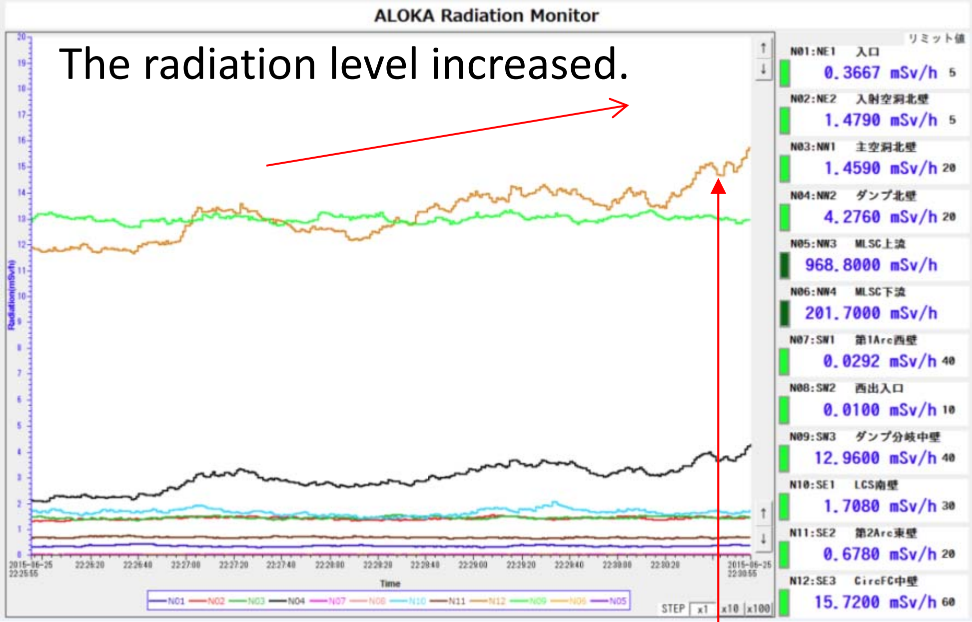
Orbit stability in CW operation :

In CW operation, orbit distortion and beam loss gradually increased.

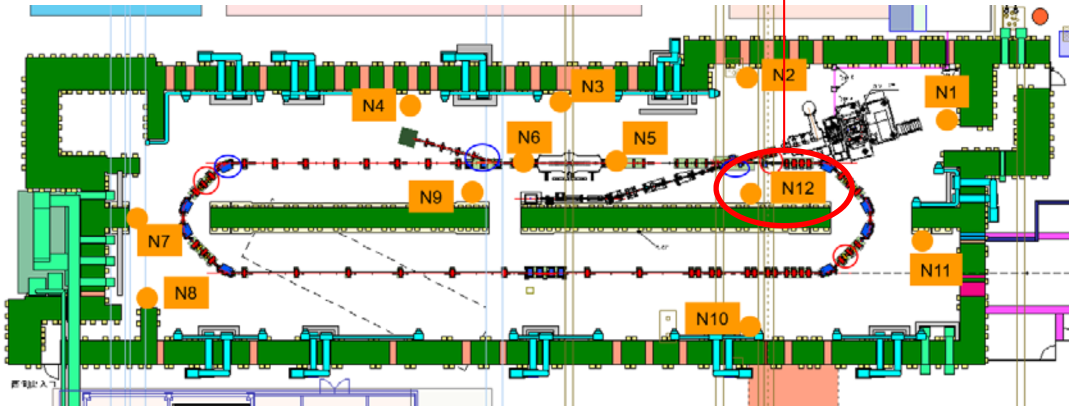
Reproducibility of beam optics : Hysteresis of magnets caused problems about reproducibility of beam optics and beam orbit.

Beam optics in recirculation loop: In the second arc section toward energy recovery, the beam optics was not well tuned. It caused beam loss.

Radiation level in previous CW operation



Area Monitors
ALOKA MAR-782

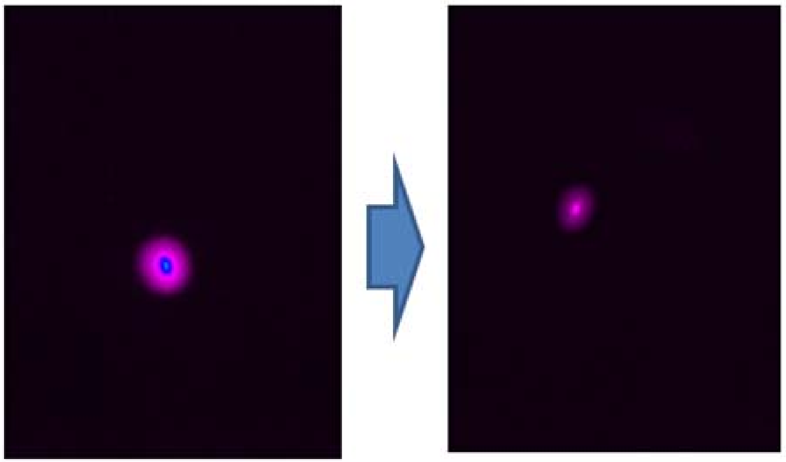


Orbit stability in CW operation

- In previous CW operation (2015), orbit distortion and beam loss gradually increased.

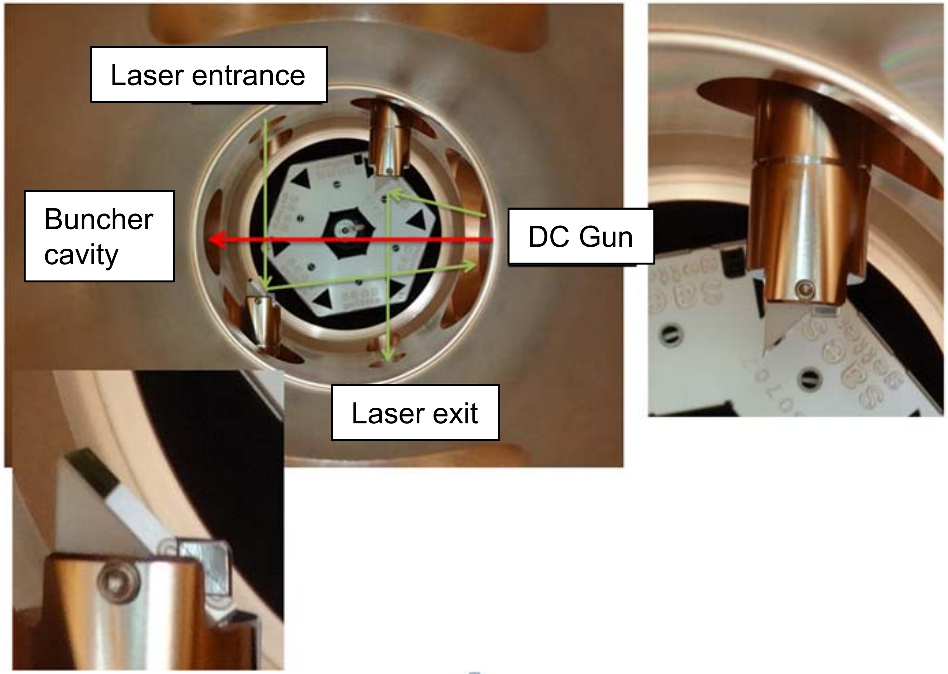
Beam profile at the entrance of injector

Before CW operation | After CW operation

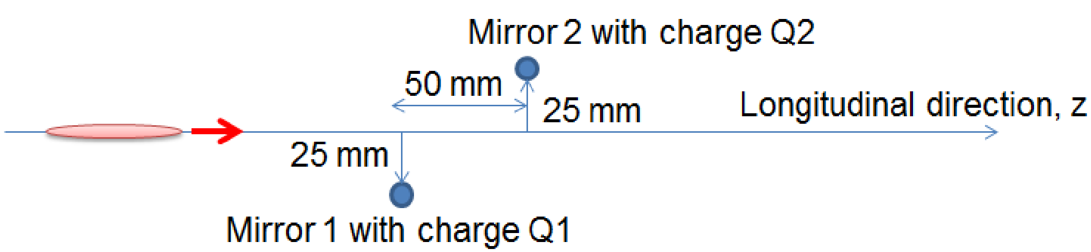


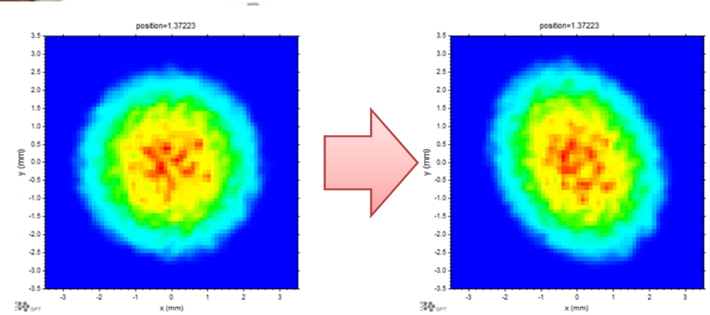
6/24 19:28 | 6/24 23:02

Charge-up of laser glass mirror?



Model simulation





Result shows that the charge-up of glass mirrors may deform the profile.

Orbit stability in CW operation

- Laser mirror made of glass was charged up, and the electric field bended the orbit of the low energy beam.

⇒ In summer 2015, we exchange the glass mirrors for metal mirrors to avoid charge-up.

Al evaporated
Glass mirror

Metal Mirror

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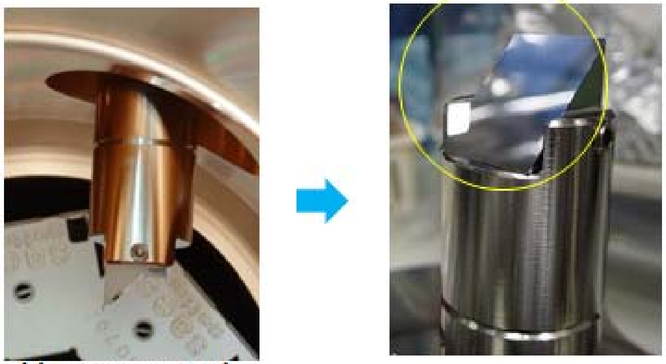


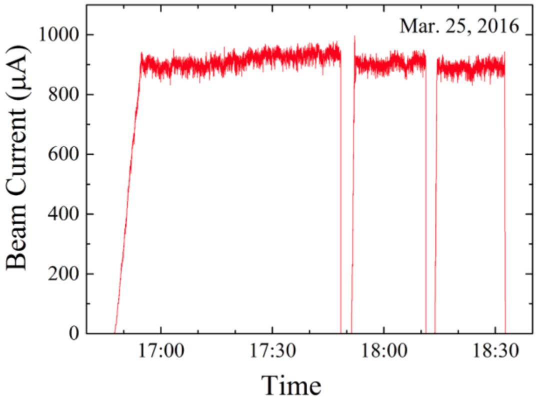
Al evaporated Glass mirror

Metal Mirror

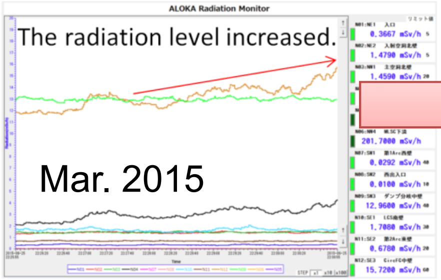
<u>CW operation in Mar. 2016</u>

Beam repetition rate：162.5 MHz

Average current: 0.9 mA (charge: 5.5 pC)

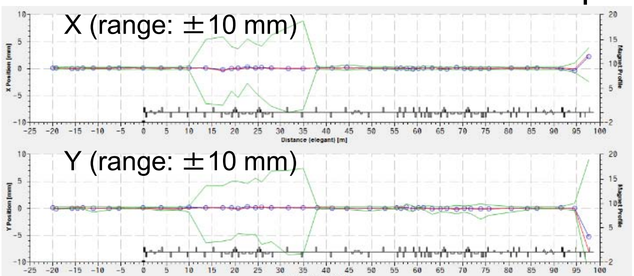


Radiation level in previous CW operation



Orbit fluctuation in CW operation (1 hour) .

Radiation level (17:44-17:49), in Mar. 2016



Result

⇒ In the CW 0.9 mA operation, the radiation level was low and very stable. Exchange mirror was very effective.

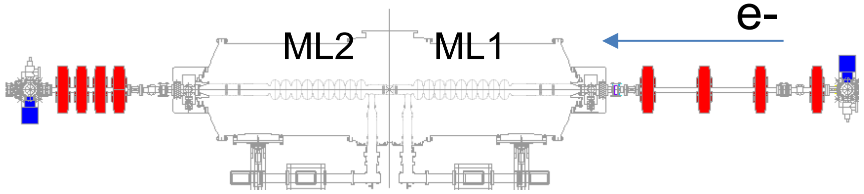
5.5 pC/bunch corresponds to CW 7 mA with 1.3 GHz.

CW 1 mA operation in June 2018

- Decreasing operation energy
  - Since 2013, the degradation of the performance of superconducting RF cavity were gradually observed.
  - In June 2018 operation, we decreased the main linac1 (ML1) acceleration voltages to avoid field emission. ⇒ The recirculation energy decreased.

Operation voltages of main linac (ML1 and ML2)

	March 2016	June 2018
ML1	10.0 MV	6.0 MV ⇩
ML2	7.2 MV	8.6 MV ⇧



Total energy (Kinetic energy)

	March 2016	June 2018
Gun	900 keV (390 keV)	1.0 MeV (500 keV) ⇧
Injector	2.9 MeV (2.4 MeV)	3.0 MeV (2.5 MeV) ⇧
Main linac	20.0 MeV (19.5 MeV)	17.6 MeV (17.1 MeV) ⇩

- Goal of CW 1 mA operation in June 2018
  - To demonstrate stable CW operation with decreased recirculation energy
  - To study beam loss control, to check the hardware performance, to check beam loss, for next CW 10 mA operation

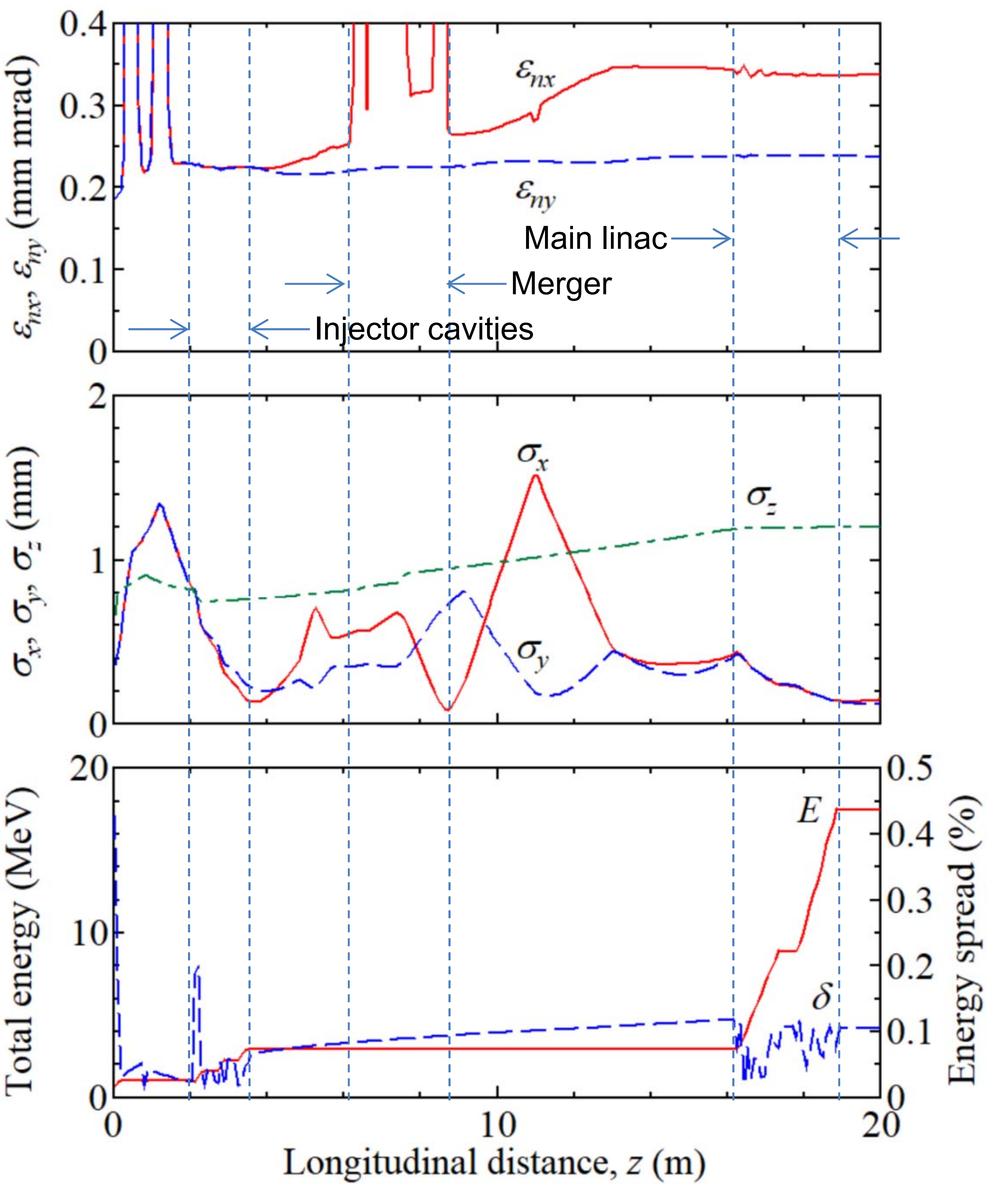
Design of injector optics

- The injector optics was optimized by using GPT and MOGA.
  - To minimize emittance and bunch length
  - To match Twiss parameters at the exit of Main linac

- Modification of accelerator model
  - Injector cavity model
  - 2D model (Poisson/Superfish model) ⇒ 3D model with input and HOM couplers (CST)
  - The effects of input and HOM couplers are not negligible.

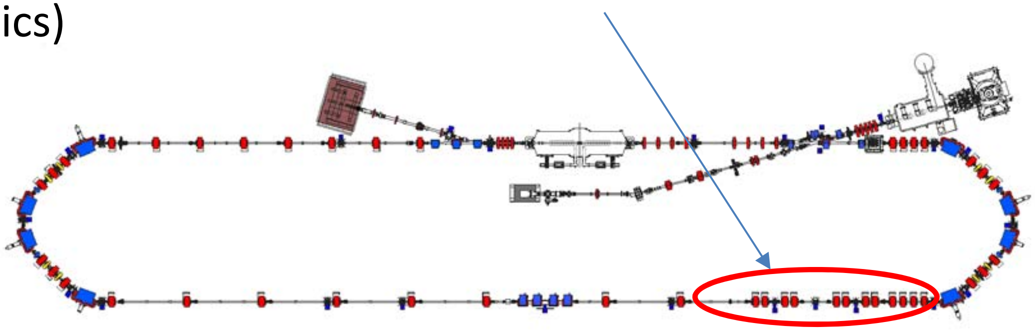
- Designed beam performance at the exit of main
  - Normalized RMS emittance :
    - enx = 0.34 mm mrad
    - eny = 0.24 mm mrad
  - RMS bunch length : 1.2 mm (4 ps)

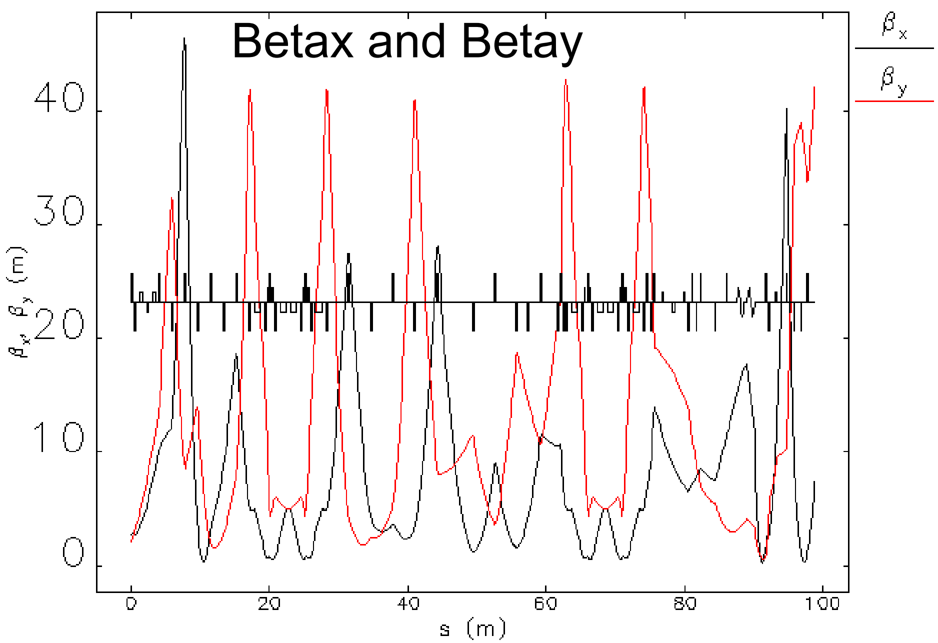
- The recirculation optics was calculated based on the optimized parameters at the exit of main linac.

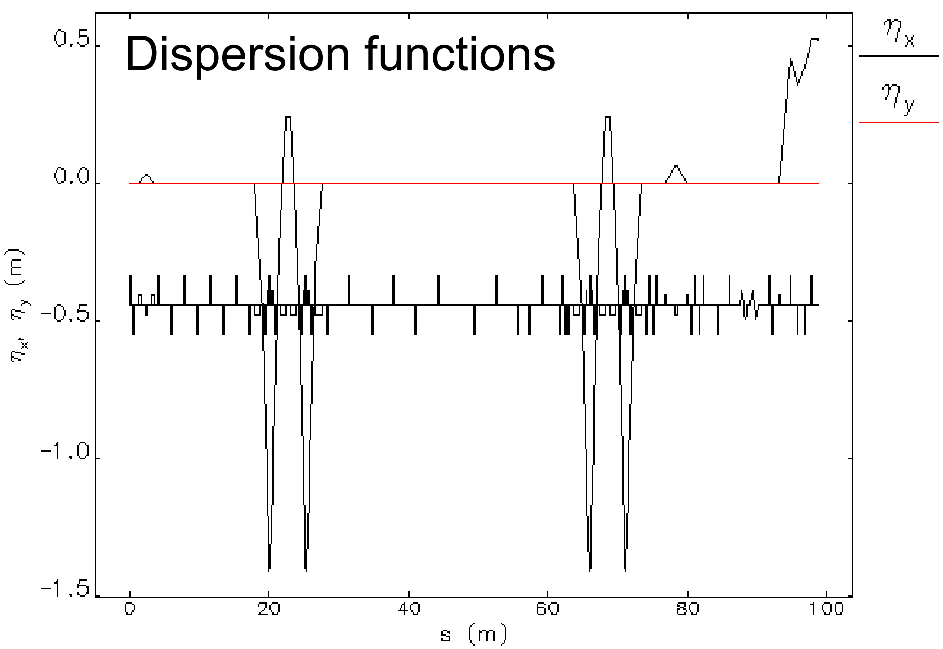


Design of recirculation loop optics

- The recirculation loop optics was designed by M. Shimada by using elegant code.
- To satisfy the energy recovery condition
- Difference from March 2016 optics: the optics in south straight section (not for Laser Compton Scattering optics)

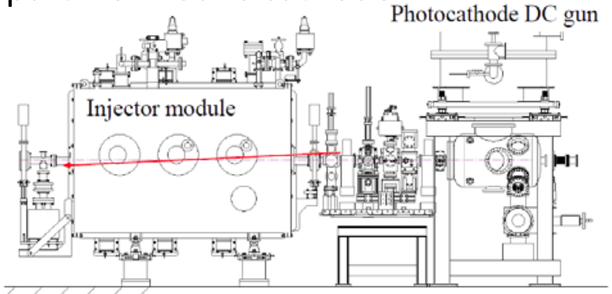






Strategy and plan for CW 1 mA operation in June 2018

- In the first 3 days: to check energy recovery operation
- In the last 6 days: to demonstrate CW 1 mA stable operation
  - Strategy
    - Based on tuning methods developed in March 2016 operation
    - Acceleration tuning, optics tuning, trajectory tuning, energy recovery tuning, dump line tuning and collimator tuning
    - Vertical trajectory offset in injector cavity to cut temporal tail part from GaAs cathode
      - The injector vertical kick depends on arrival time difference.
      - The tail part is kicked for vertical direction.
      - The tail part is cut by collimator.



  - Plan in the first 3 days
    - 6 June: Gun and injector tuning
    - 7 June: Merger and Main linac optics matching, 17 MeV acceleration tuning
    - 8 June: Trajectory and optics tuning in the recirculation loop, energy recovery tuning, and collimator tuning
  - Plan in the last 6 days
    - 22 June: Injector optics tuning, vertical offset tuning
    - 25 June: energy recovery and CW operation tuning
    - 26 June: CW operation tuning, beam halo measurement, THz and RCDR measurement
    - 27 June: CW operation tuning, radiation survey in CW 1 mA operation
    - 28 June: recirculation optics study
    - 29 June: test of high voltage power supply of DC gun

CW 1 mA tuning in the first 3 days

- In the first 3 days: We achieved energy recovery operation (not CW operation) as scheduled plan
- In the last 5 days: We required a lot of tuning to reduce beam loss…

Design

	March 2016	June 2018
Gun	900 keV (390 keV)	1.0 MeV (500 keV)
Injector	2.9 MeV (2.4 MeV)	3.0 MeV (2.5 MeV)
Main linac	20.0 MeV (19.5 MeV)	17.6 MeV (17.1 MeV)

Operation energy

EnergyDisp.opi

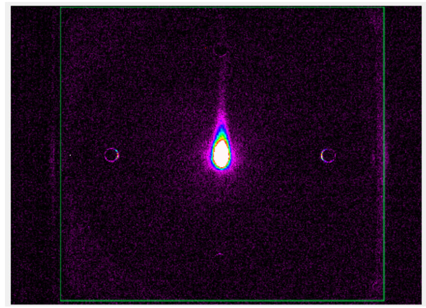
Energy Disp (for K value) / Energy Calculator

	GUN	INJ	CIR		calc
Total Energy I	1.011	2.95	17.68	MeV	100
Kinetic Energy	0.5	2.439	17.169	MeV	99.489
momentum P (pc	0.872	2.905	17.673	MeV/c	99.999
P ratic		1 :	6.0827		
gamma	1.9785	5.773	34.5988		195.6947
beta	0.8629	0.9849	0.9996		1

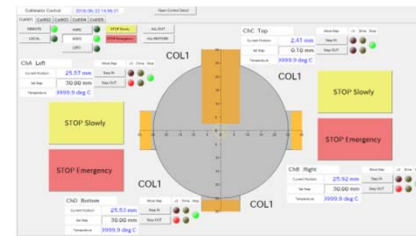
The measured energies were the same as the designs.

Injector trajectory offset tuning

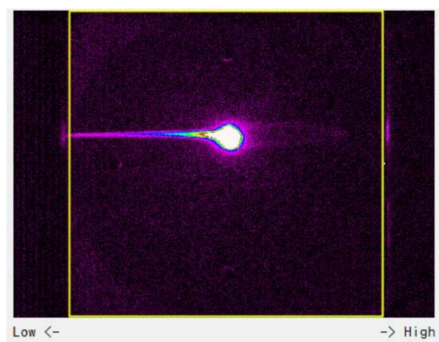
- To kick tail part for upper direction



Beam profile at the exit of injector cavity



Beam profile in merger without collimator

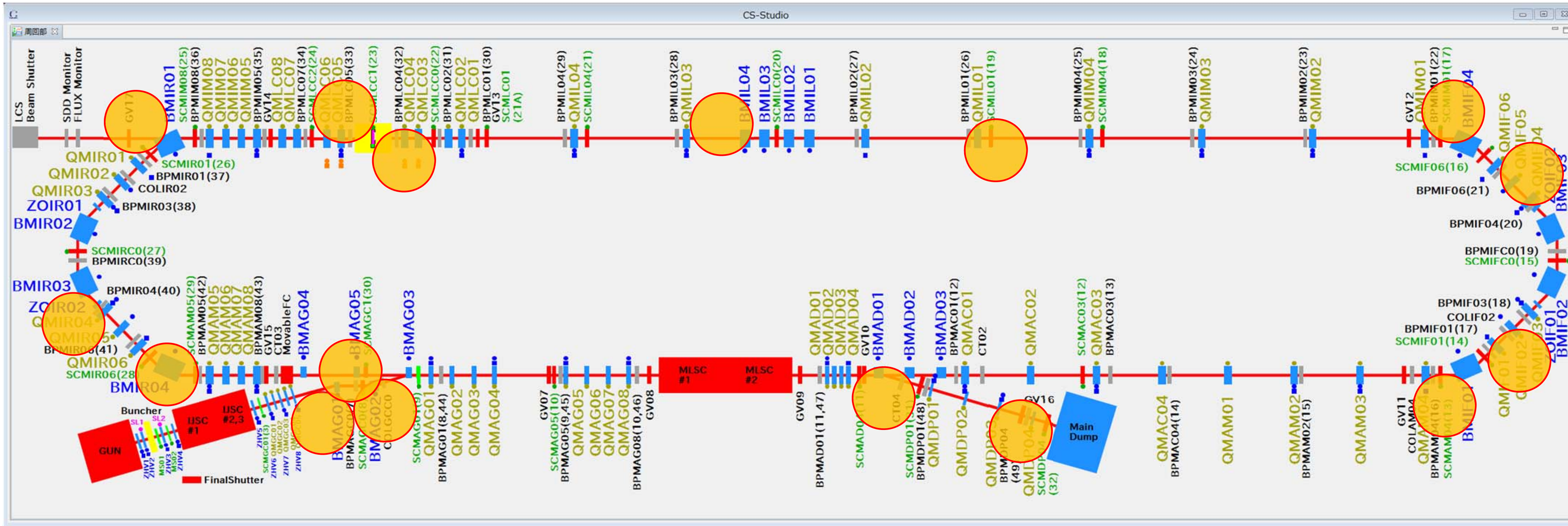


With collimator at the exit of injector cavity

It was effective to cut the energy tail. However, it was not effective to reduce beam loss in the recirculation loop…

Loss monitors for interlock

- Number of loss monitors for interlock: 16
- The loss monitors are also used for diagnosis and beam tuning.



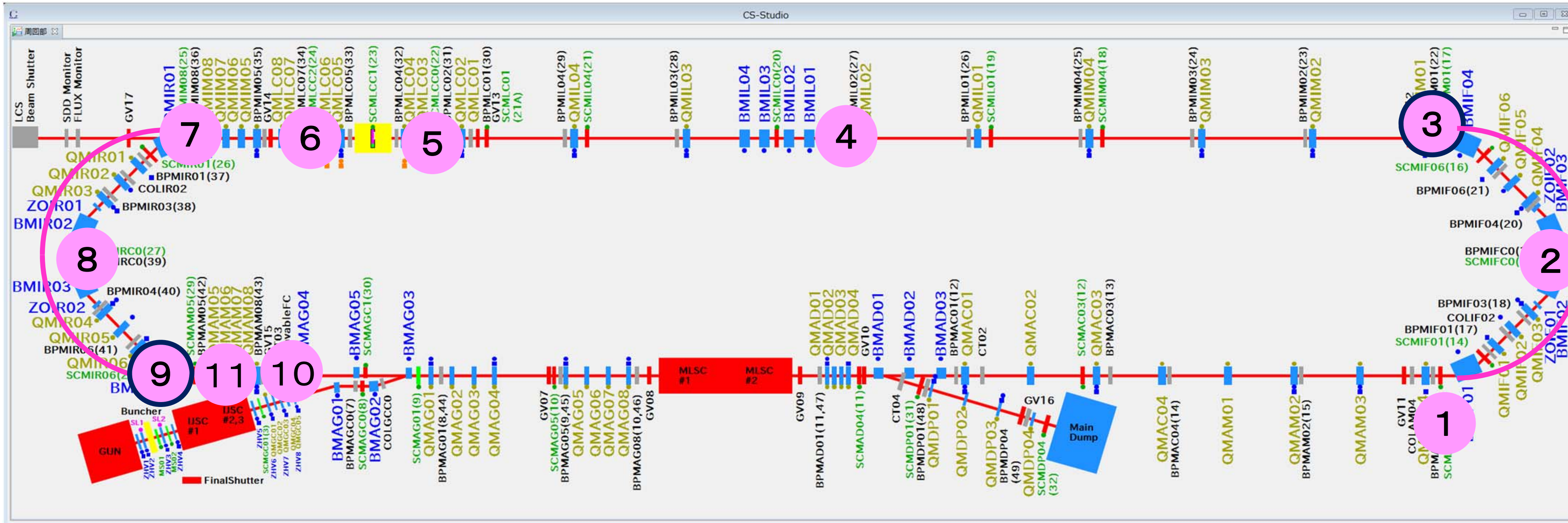
Detector
Pure CsI
+ PMT

preAmp

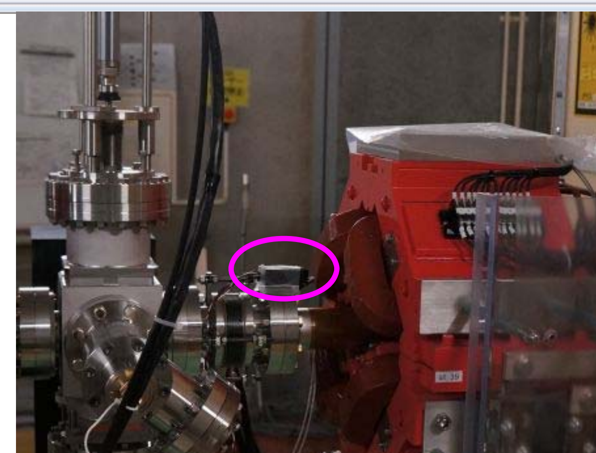
Fast Interlock System

Loss monitors for diagnosis

- Scintillator CsI(Tl) + PMT : 9
- Optical fiber + PMT (#3, #9): 2

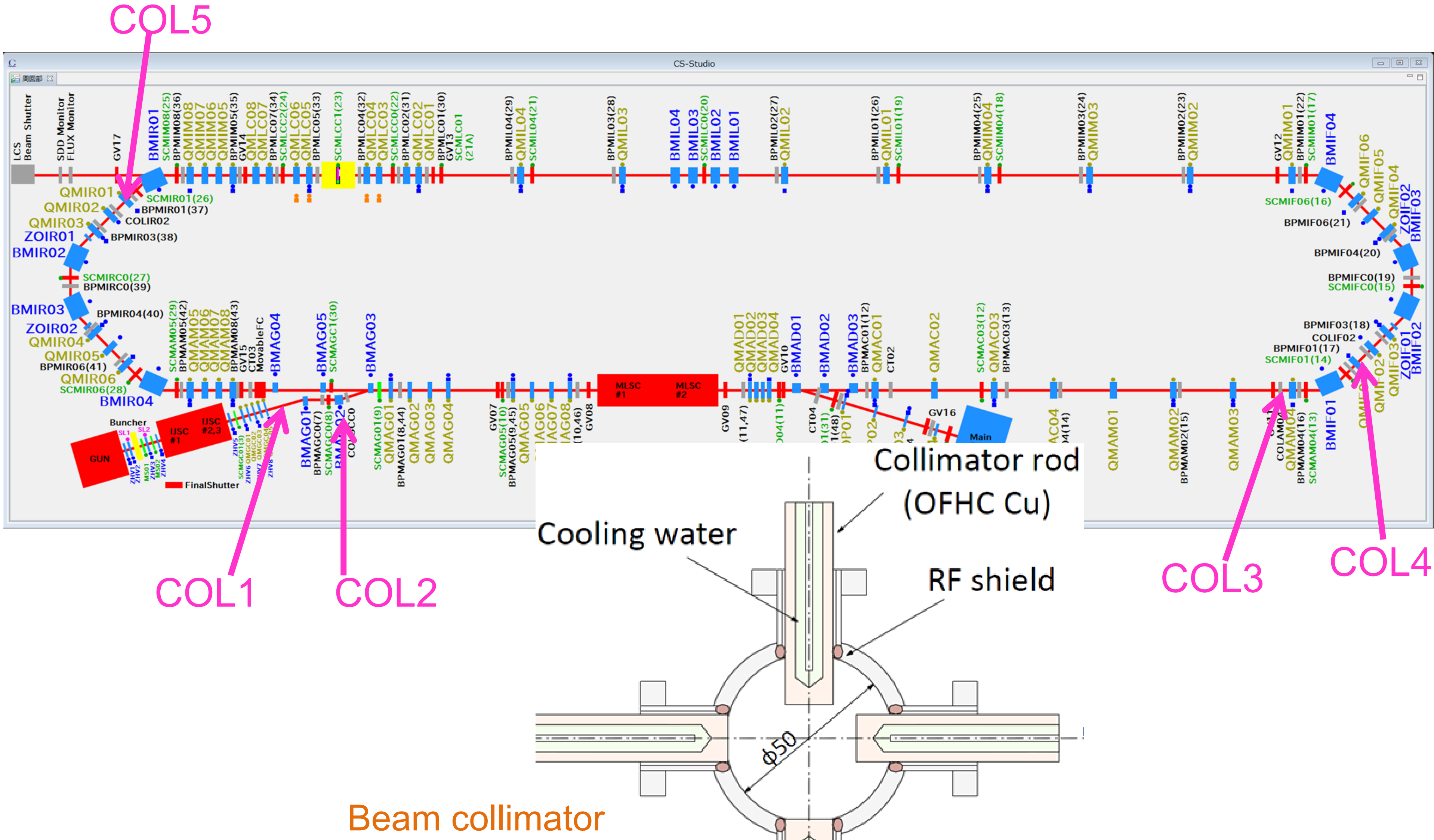


Detector



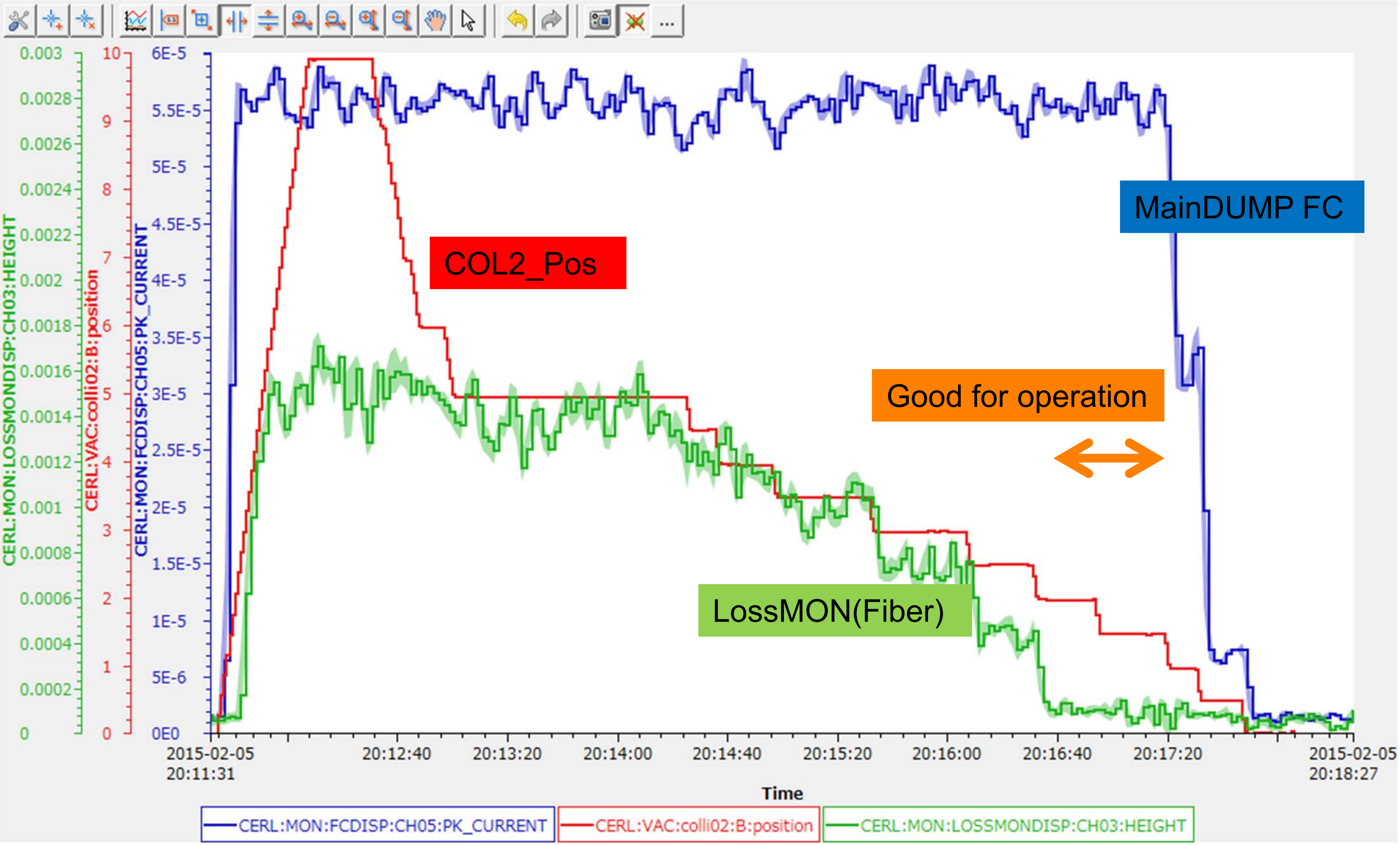
Collimators

- COL1 and COL2 in injector, COL3 and COL4 in the first arc section, COL5 in the second arc section



Beam collimator

Collimator tuning in burst mode



History of beam loss tuning

- To achieve stable CW 0.9 mA operation, we continued beam loss tuning using loss monitors and collimators.

Trial	Date	Maximum current (mA)	
1	25 June, 1	0.025	
2	25 June, 2	0.024	
3	25 June, 3	0.023	
4	26 June, 1	?	
5	26 June, 2	0.03	
6	26 June, 3	0.1	
7	26 June, 4	0.01	
8	26 June, 5	0.16	
9	27 June, 1	0.14	
10	27 June, 2	0.35	
11	27 June, 3	0.3	
12	27 June, 4	0.35	
13	27 June, 5	0.33	
14	27 June, 6	0.85	
15	27 June, 7	0.85	
16	29 June, 1	0.3	
17	29 June, 2	0.6	
18	29 June, 3	0.9	OK
19	29 June, 4	0.9	OK

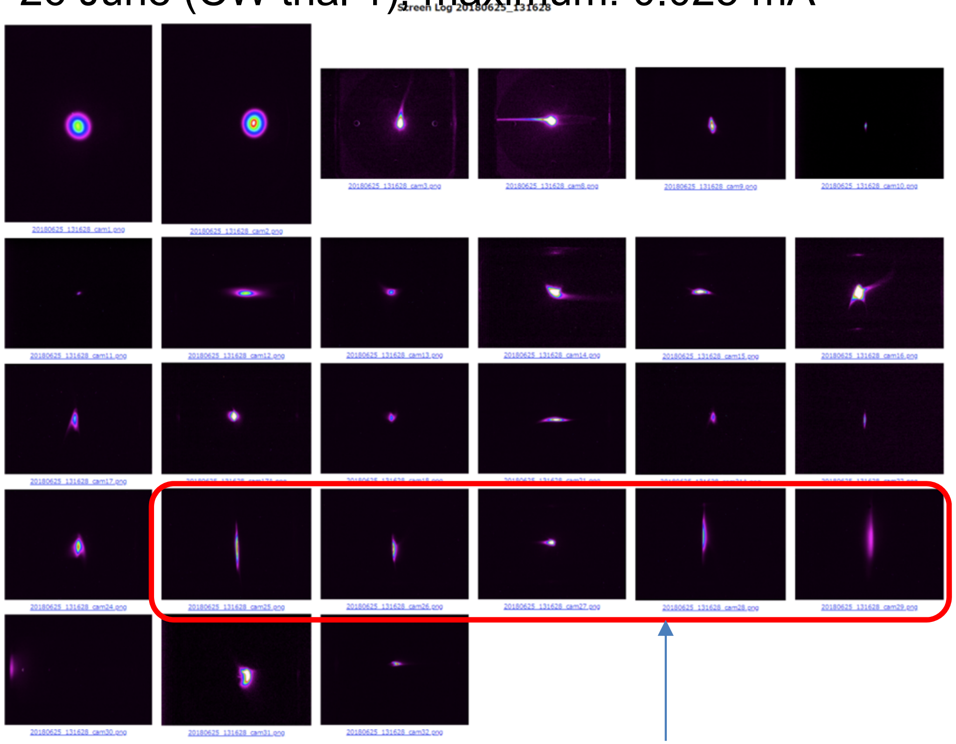
- Effective items to achieve stable CW 0.9 mA operation
  - Optics tuning in the second arc section ⇒ The beam loss around the gun decreased.
  - Adjustment of circumference (energy recovery timing) ⇒ The beam loss around the beam dump decreased.
  - R56 and achromatic condition tunings in the second arc section. ⇒ The beam loss around the dump chicane decreased.
  - Decelerated beam tuining ⇒ The beam loss around the dump chicane decreased.
  - Collimator tuning ⇒ The next important topic is to study the relation between collimator and beam loss point.

- In June 2018 CW operation, the injector vertical offset was not effective.

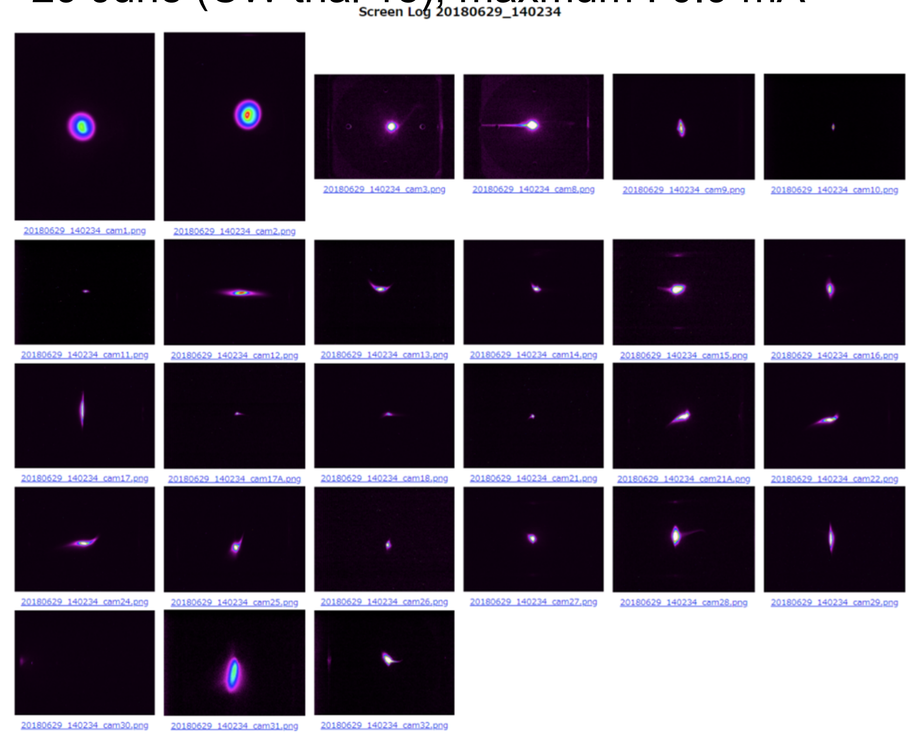
Beam profiles

- Compering beam profiles for the first trial and stable CW 0.9 mA operation

26 June (CW trial 1), maximum: 0.025 mA



29 June (CW trial 18), maxmum : 0.9 mA

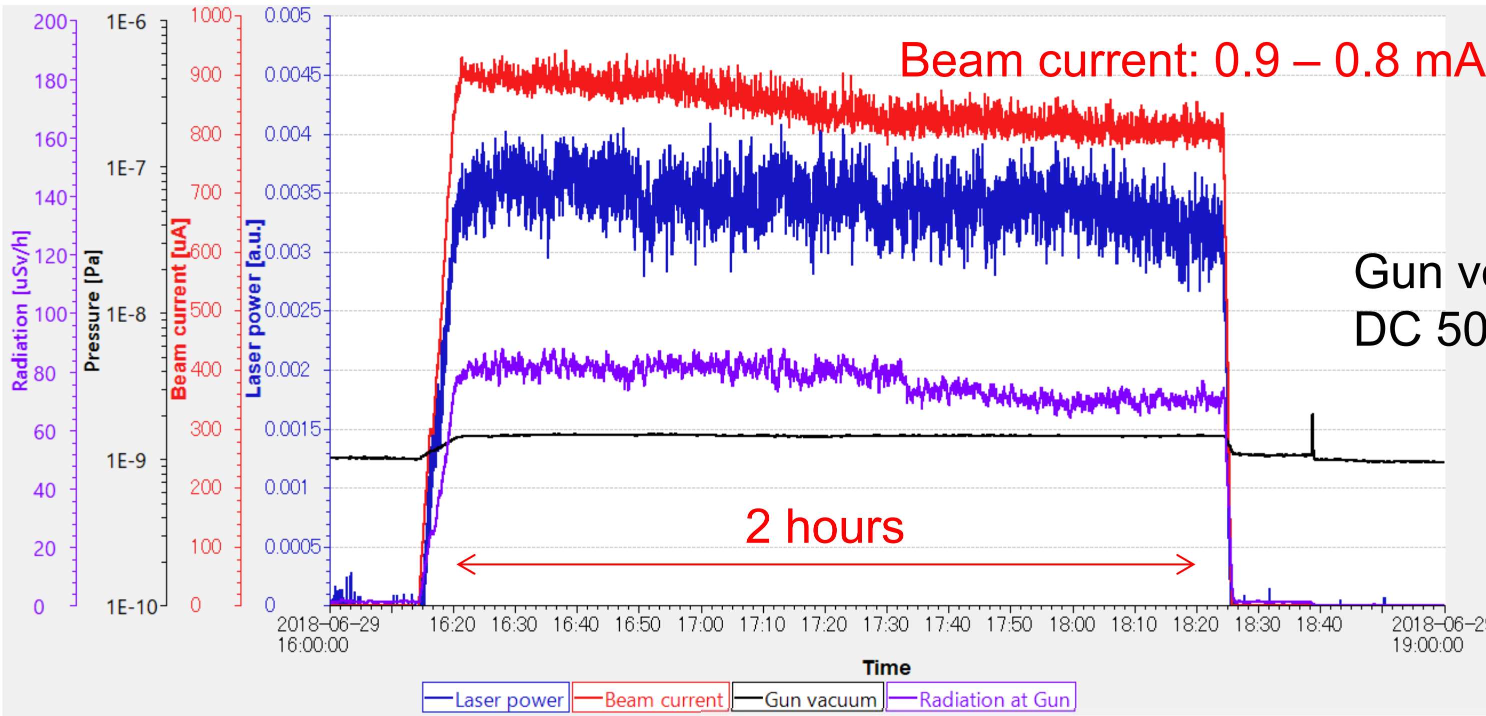


- Beam profiles around the second arc section
  - In CW trial 1: the vertical beam sizes were lager than design values.
  - In CW trial 18: the profiles were very close to designed profile.

- Important tuning items:
  - Beam optics around the second arc section, circumference, R56, achromatic condition and collimator

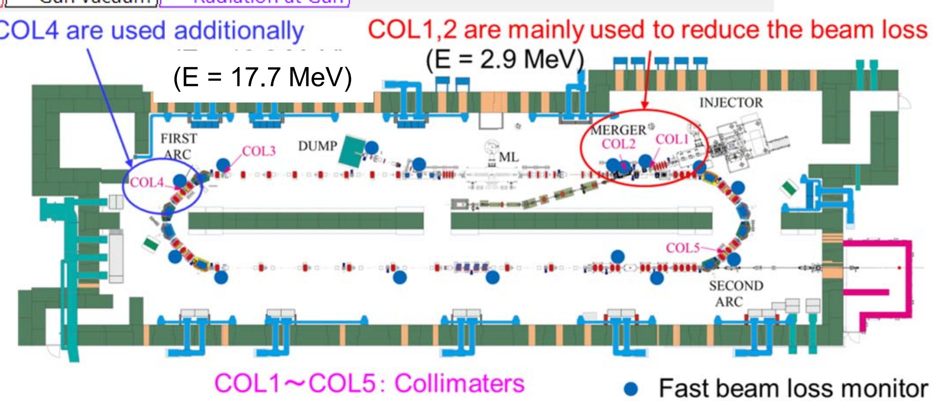
CW 1 mA operation, June 2018

- After the fine beam loss tuning, we succeeded in CW 0.9 – 0.8 mA operation. It was very stable in 2 hours.



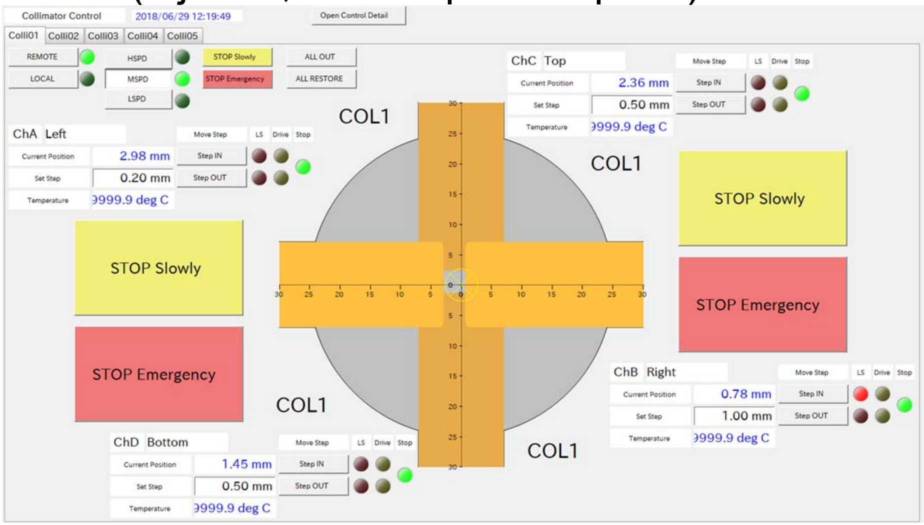
Gun voltage:
DC 500 kV

- Before CW operation: we adjusted the optics and collimators in pulse operation with low average current.
- In the CW operation: we can not change any parameter. To keep CW beam current, we increased laser power for photocathode.

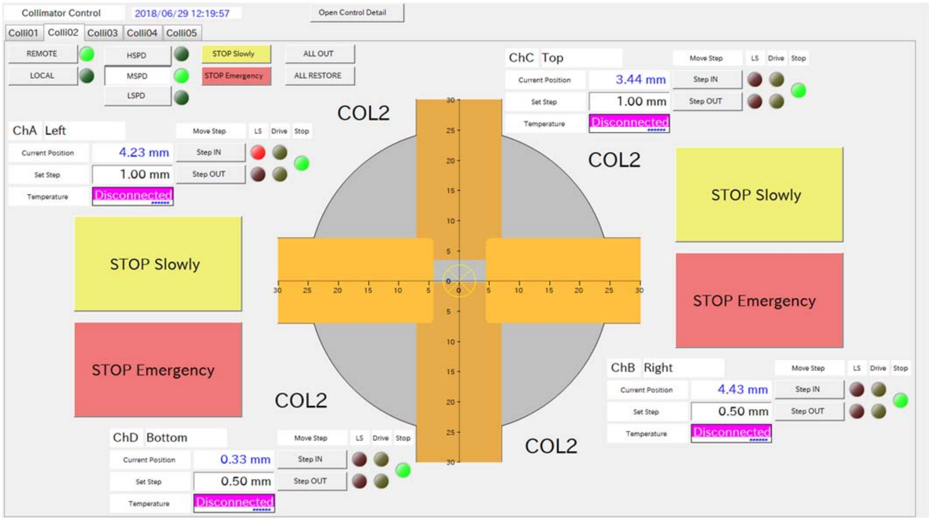


Effect of collimator for CW 1 mA operation

COL1 (Injector, non-dispersive point)

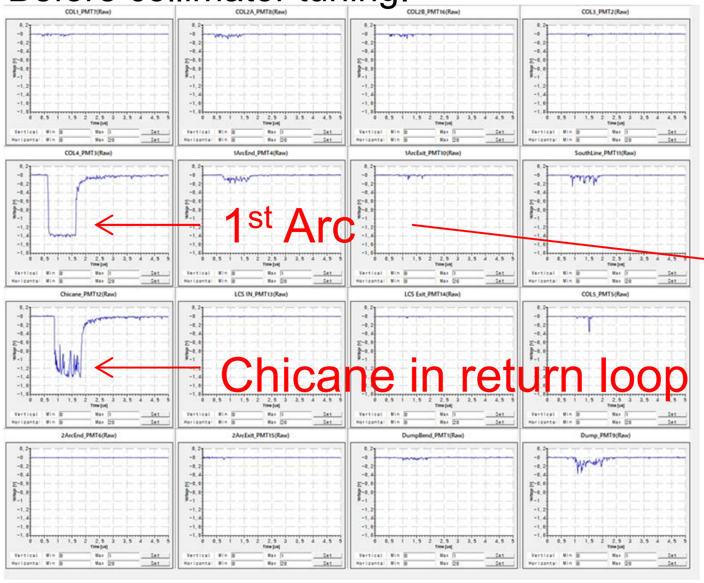


COL2 (Merger, dispersive point)



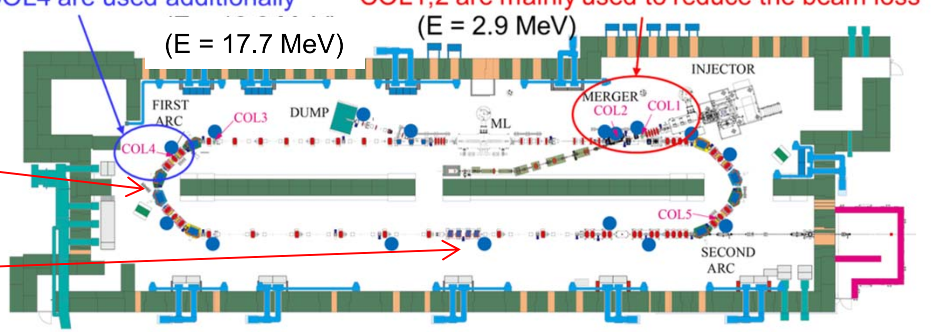
Los monitor signals

Before collimator tuning.



COL4 are used additionally (E = 17.7 MeV)

COL1,2 are mainly used to reduce the beam loss (E = 2.9 MeV)

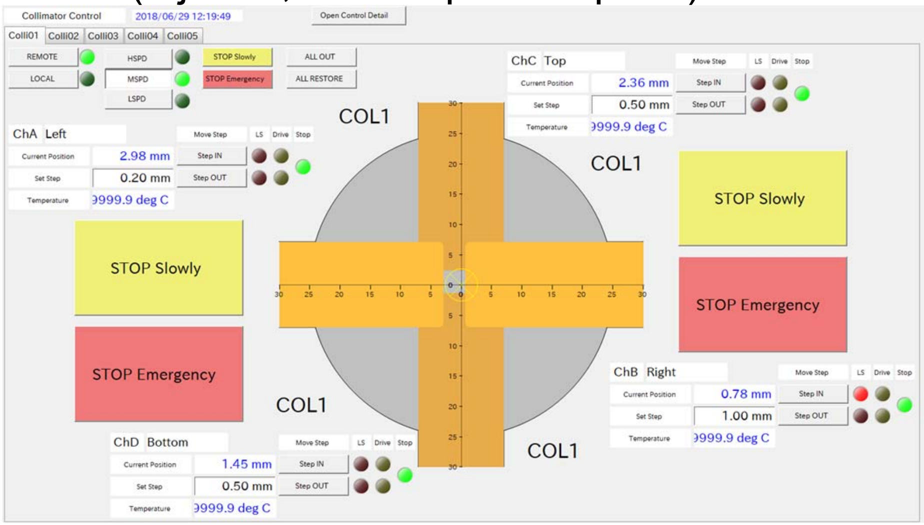


COL1～COL5: Collimaters

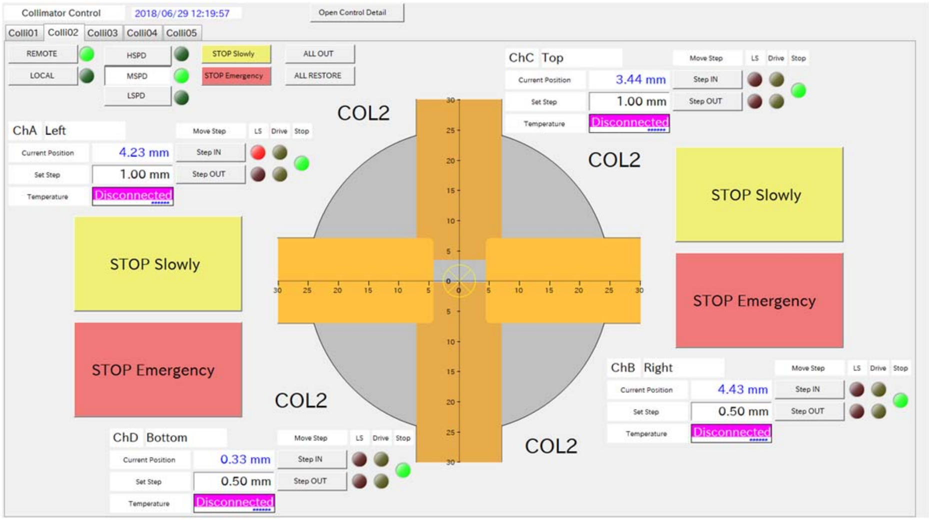
● Fast beam loss monitor

Effect of collimator for CW 1 mA operation

COL1 (Injector, non-dispersive point)

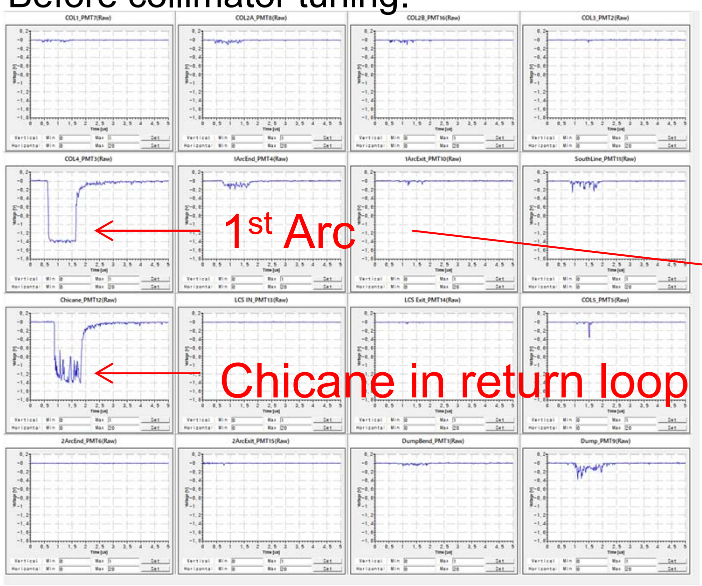


COL2 (Merger, dispersive point)

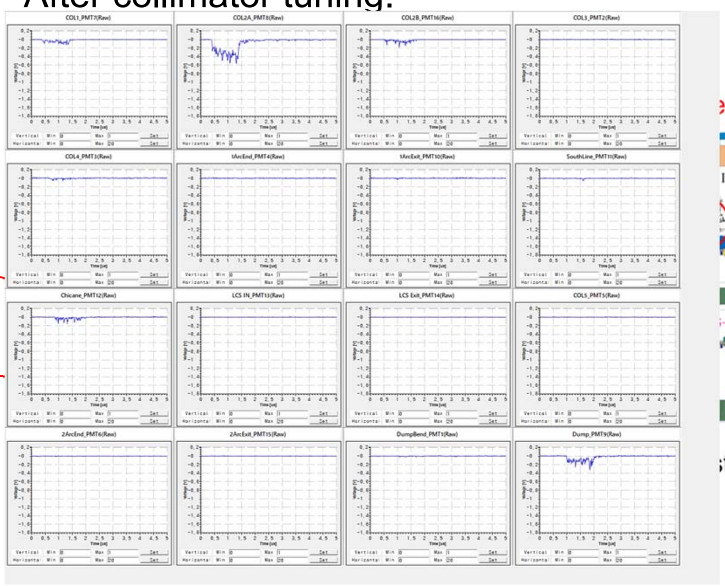


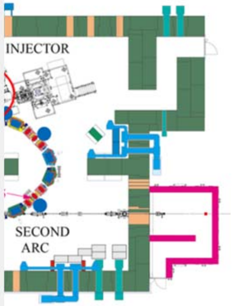
Los monitor signals

Before collimator tuning.



After collimator tuning.

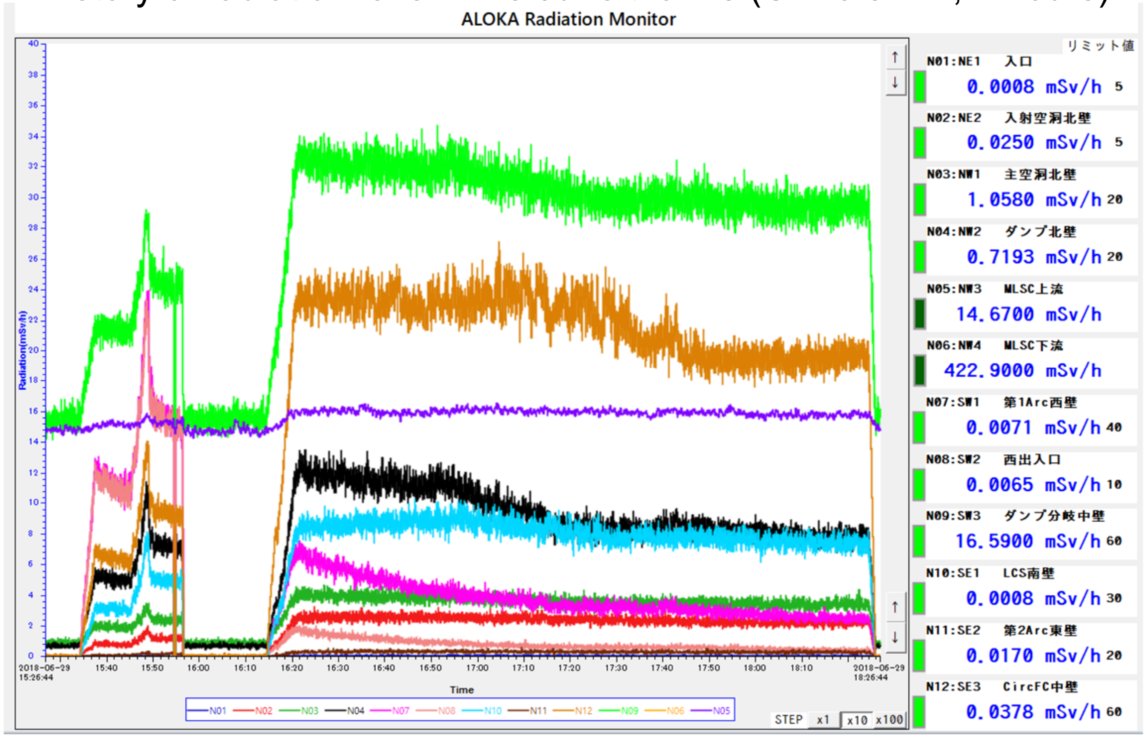




Result of CW 1 mA operation in June 2018

- After fine beam loss tuning, we achieved stable CW 0.9 mA operation with 17.6 MeV recirculation energy in 2 hours.
- Beam trajectory, radiation level and rastering system were stable.
- We did not require the injector trajectory offset to mitigate beam loss.
- Important tuning items: beam optics, R56, achromatic condition in the second arc section, deceleration tuning, beam dump tuning
- After optics tuning, the fine collimator tuning was very important.

History of radiation level in 29 June trial 28 (CW 0.9 mA, 2 hours)



Beam performance:

<u>Design in recirculation loop</u>

enx = 0.34 mm mrad

eny = 0.24 mm mrad

<u>Measured emittance by Q-scan method</u>

North straight section:

(H, V) = (0.29, 0.26) umrad

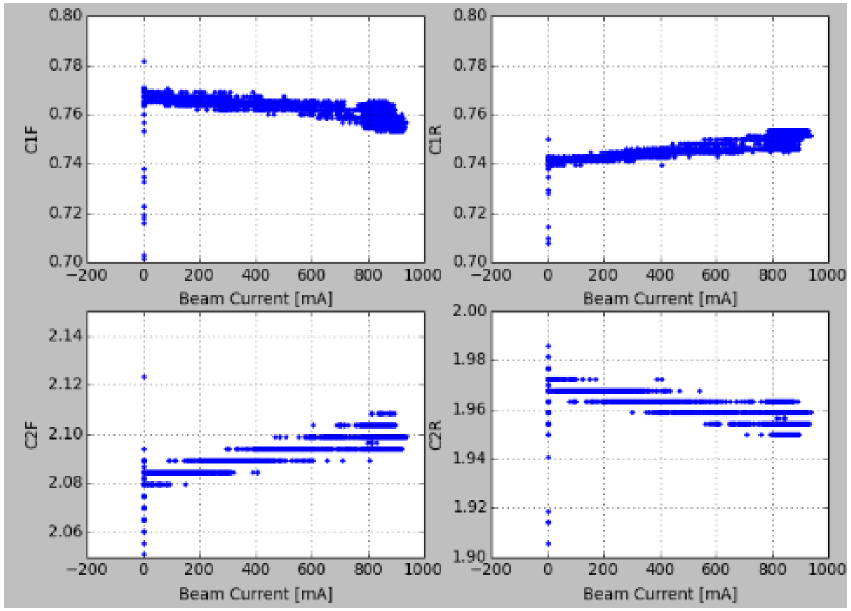
South straight section:

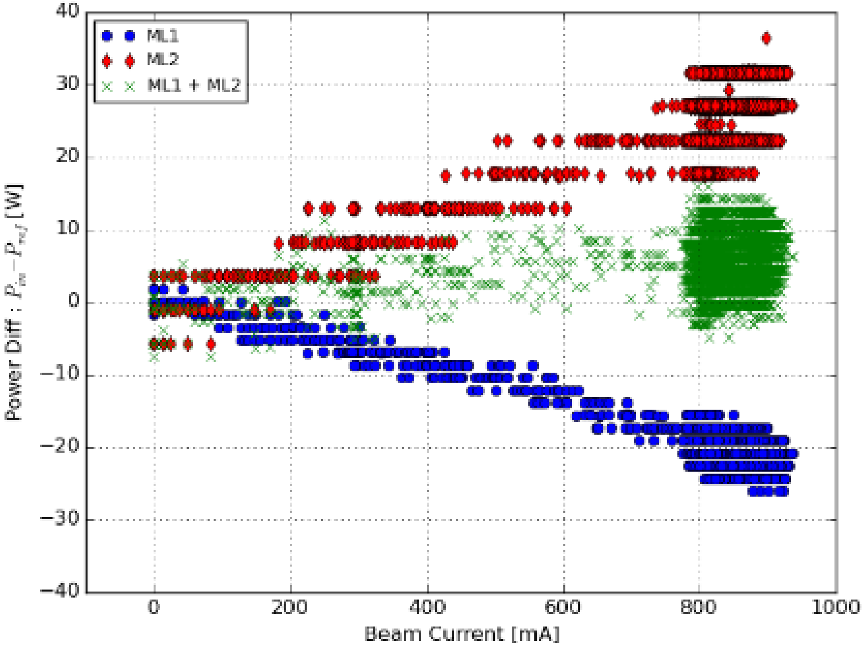
(H, V) = (0.42, 0.26) umrad

The measured emittances were close to design values.

Energy Recovery Efficiency

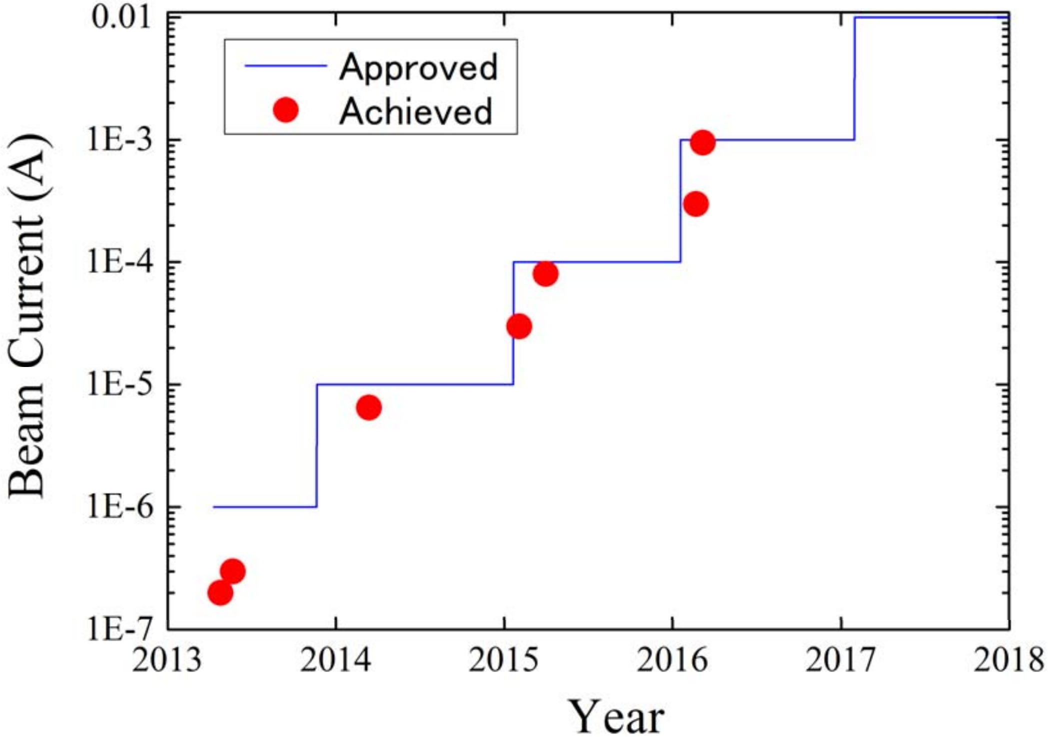
The difference in the cavity forward power and reflected power (Pin - Pref) of ML1 and ML2 with respect to the average beam current.



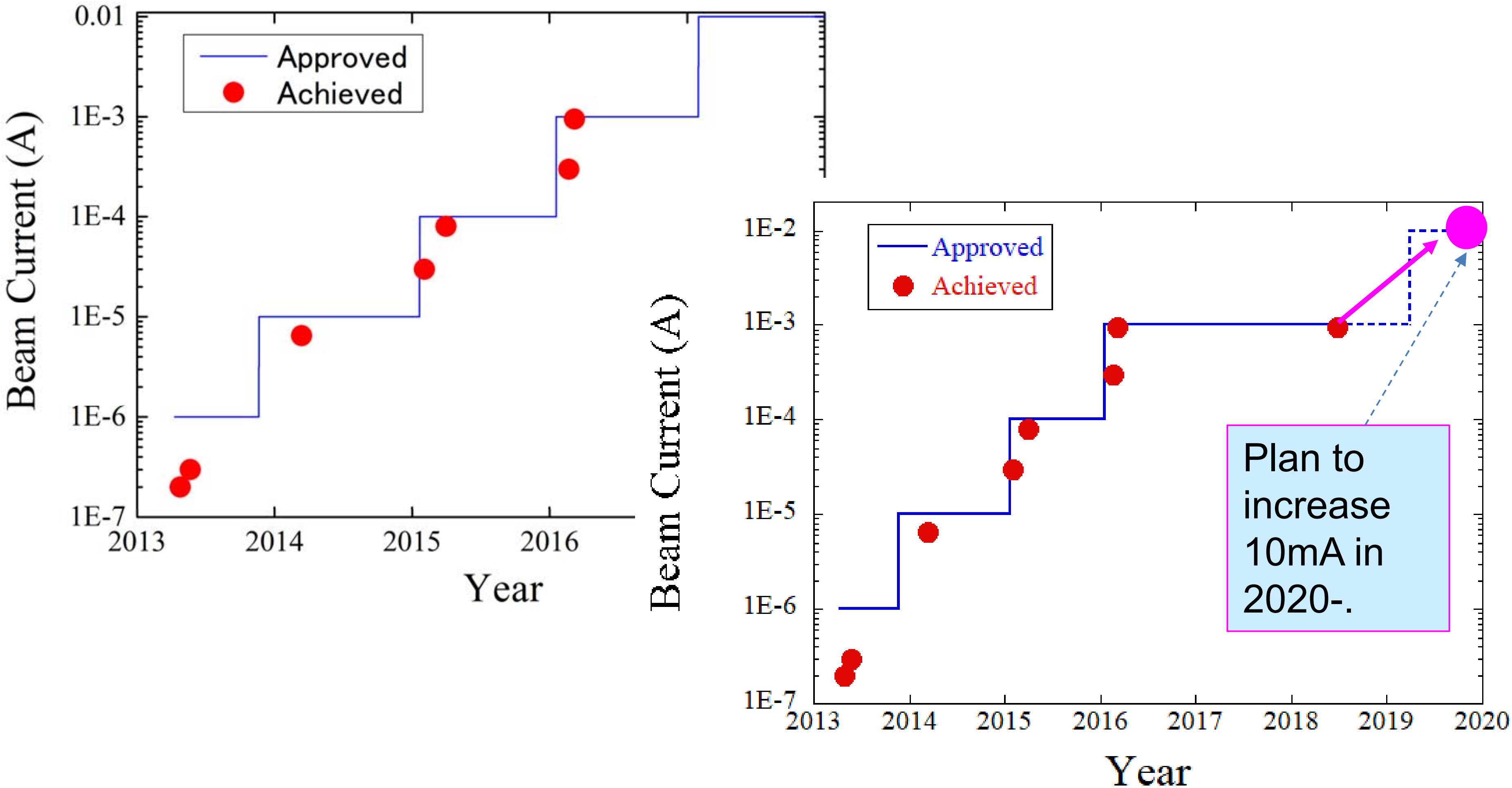


- The value indicates the efficiency of energy recovery and goes to zero in case of 100% recovery.
- It is clear that the difference in power is extremely smaller than the power without energy recovery, namely, 8.6 kW.
- The recovery efficiencies are estimated to 100.35% in ML1 and 99.65% in ML2 due to the fact that the velocity of electron beam is not exactly equal at the first and the second passages through the cavities.
- In total of two cavities, power recovery is estimated from the sum of the two difference : ML1(Pin - Pref) + ML2(Pin - Pref),to be 100% +/- 0.05 %.

Beam Currents: Achievement and Prospect



Beam Currents: Achievement and Prospect



By achieving low loss beam operation and low emittance beam generation of 7.7pC, CW 10 mA operation is within target.

Summary

- In June 2018, we succeeded to CW 0.9 mA operation with recirculation loop energy 17.6 MeV after fine beam loss tuning. It is stable in 2 hours.
- To achieve stable CW operation, optics tuning and collimator tuning were very important.

- Beam performance:
  - The measured emittances were close to design values.
  - Energy recovery efficiency was 100% +/- 0.05 %.

- Future plan for Energy Recovery CW operation
  - 2020-, CW 10 mA operation test (maximum average current: 1 mA to 10 mA)

- Toward to CW 10 mA operation
  - In 2019, we are improving the high voltage power supply of the DC gun
  - Beam halo measurement to understand the mechanism
  - Wake field caused by collimator
  - Cathode QE degradation for GaAs photocathode (Off center operation)
  - Reproducibility of beam loss tuning and collimator setting

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Thank you for your attention!