THIACC001

Higher bunch charge operation in compact ERL at KEK

8:30-8:55, 22 June, 2017
ERL17, CERN (Geneva)

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

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Outline

- Introduction
  - Layout, components, operation history of cERL at KEK
- 5.5 pC bunch charge, 0.9 mA CW ERL operation (March, 2016)
- 60 pC bunch charge, non-ERL operation (March, 2017)
- Summary

Introduction

cERL Team

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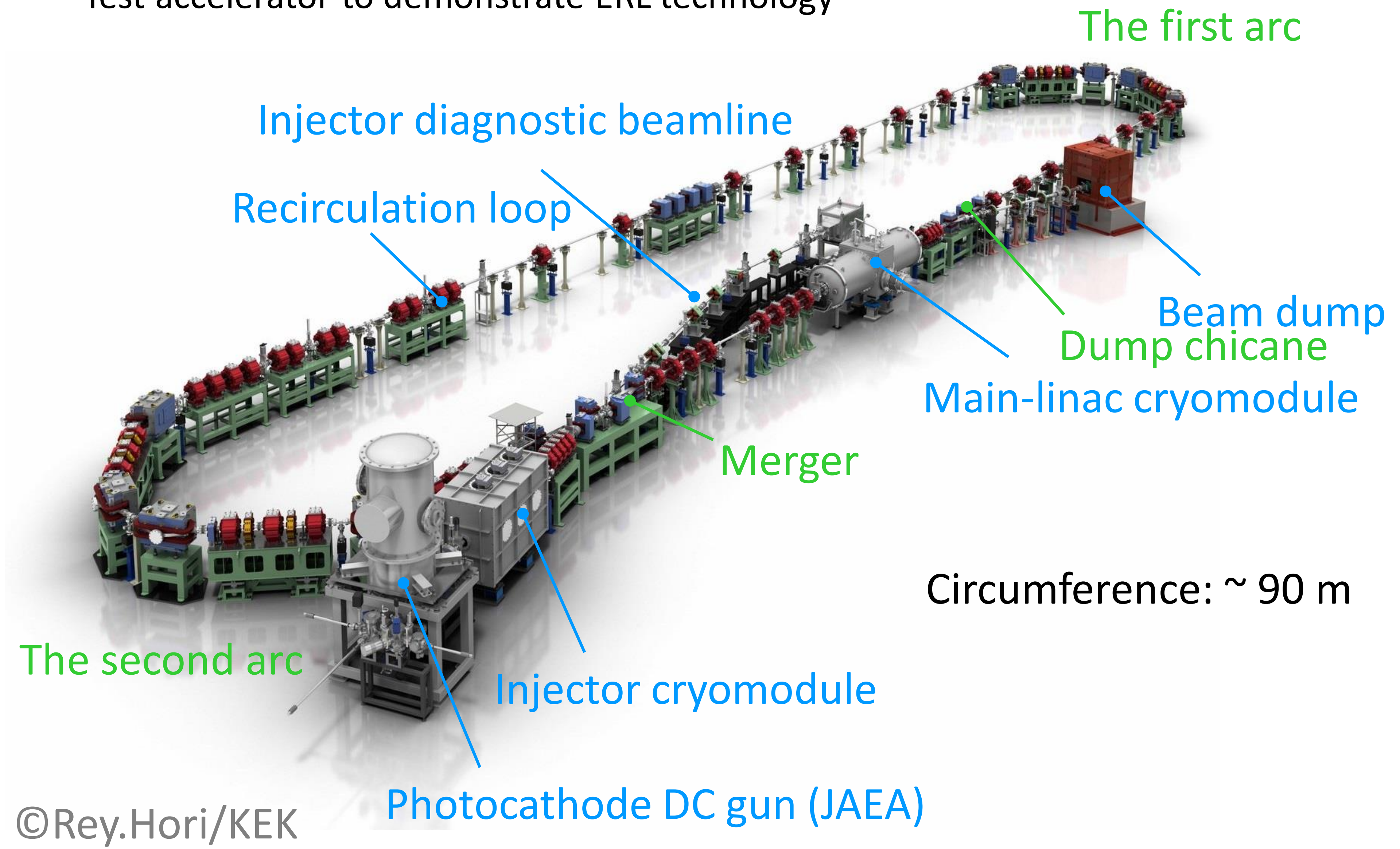
Compact ERL

- Test accelerator to demonstrate ERL technology



Circumference: ~ 90 m

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

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

5.5 pC bunch charge, 0.9 mA CW ERL operation in March 2016

Problems of previous operation in 2015

Previous operation in 2015

- CW operation: Average current 0.075 mA（charge: 0.46 pC, 162.5 MHz）
- 7.7 pC operation (not CW operation)

Orbit stability in CW operation :

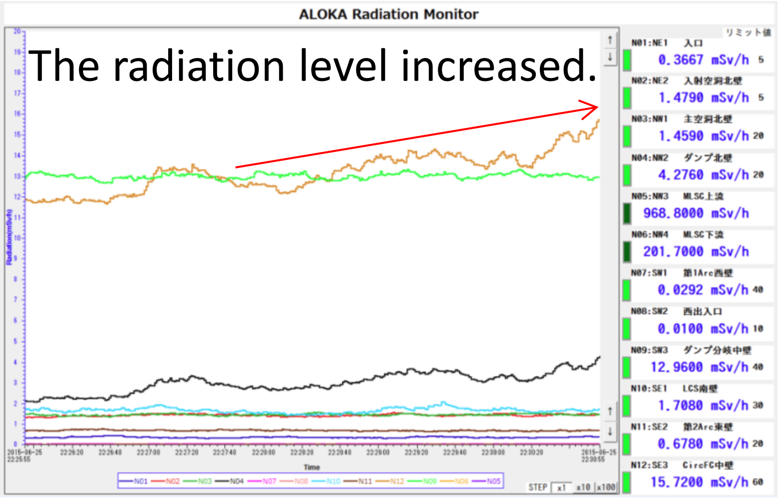
In CW operation, orbit distortion and beam loss gradually increased.

Asymmetry of beam profile after the DC photocathode gun : For 7.7 pC operation(not CW operation) , the cylindrical symmetry of transverse beam profile was broken.

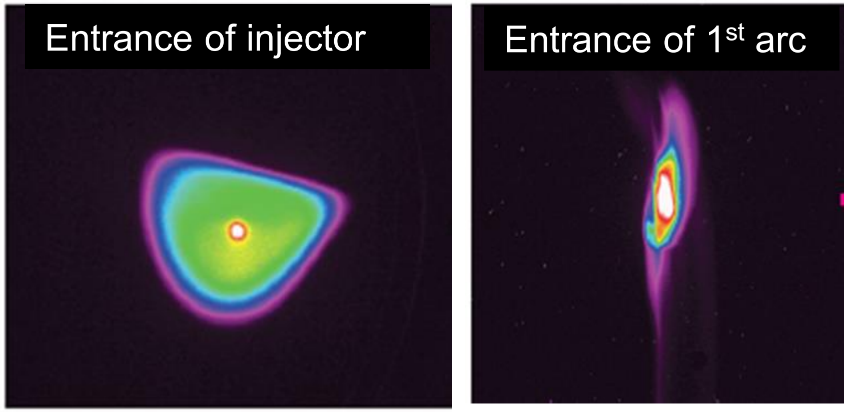
Reproducibility of beam optics : Hysteresis of magnets caused problems about reproducibility of beam optics and beam orbit.

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



Transverse beam profiles (7.7 pC)

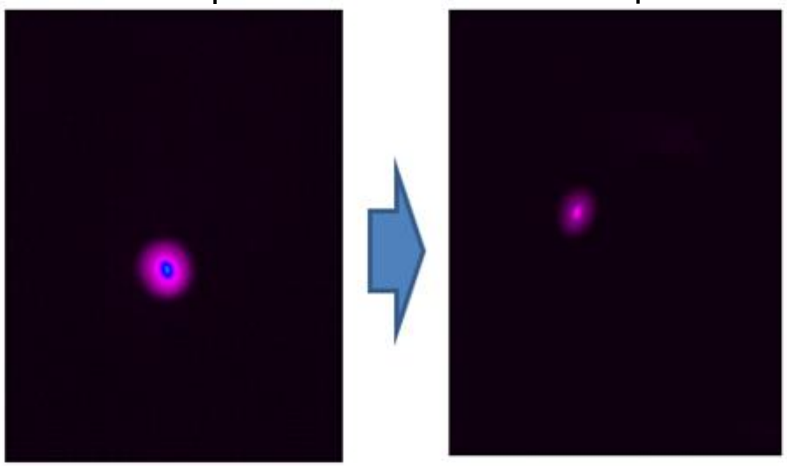


Orbit stability in CW operation

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

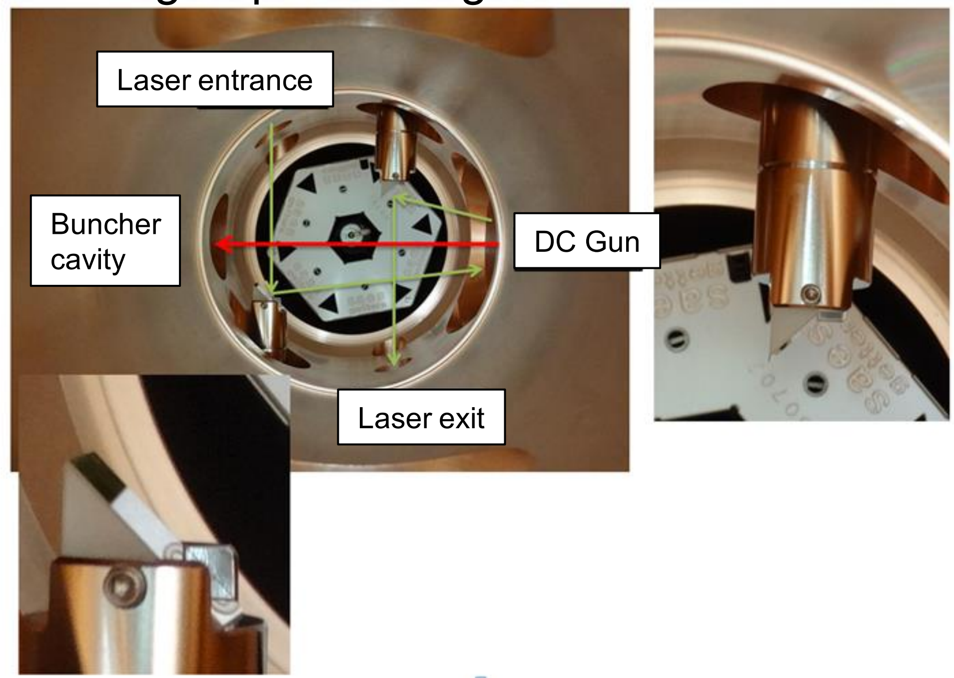
Beam profile at the entrance of injector

Before CW operation | After CW operation

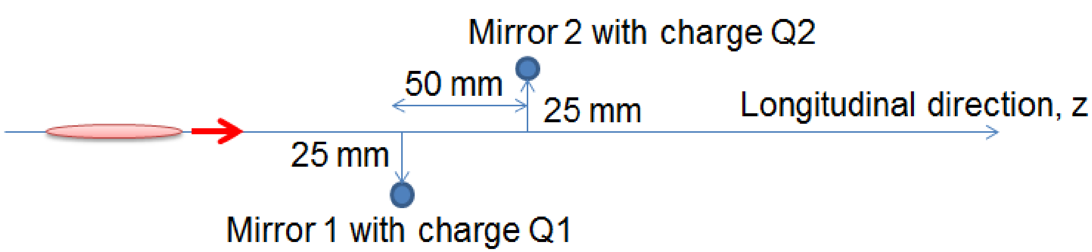


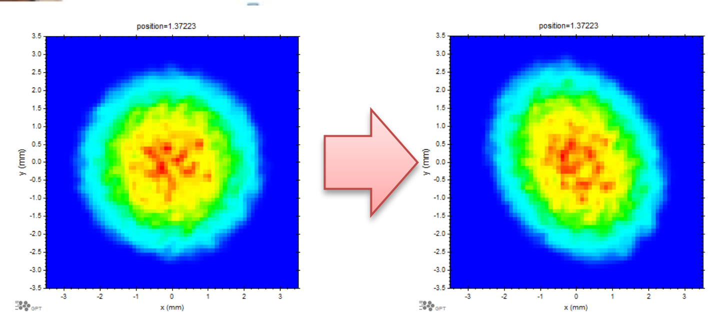
6/24 19:28 | 6/24 23:02

Charge-up of laser glass mirror?



Model simulation



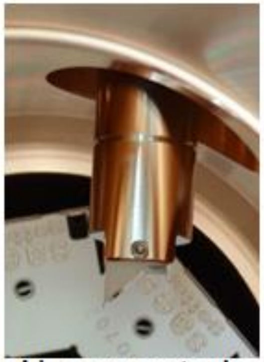


Result shows that the charge-up of glass mirrors may deform the profile.

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.



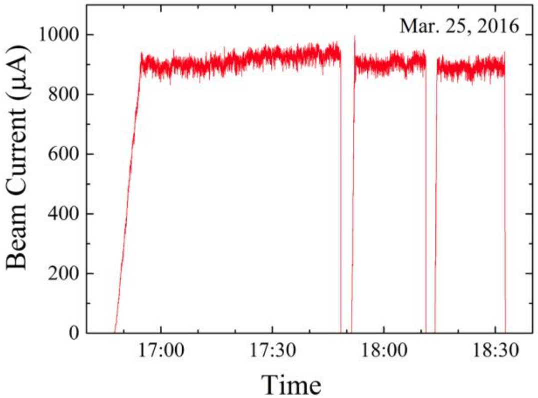
Al evaporated Glass mirror

Metal Mirror

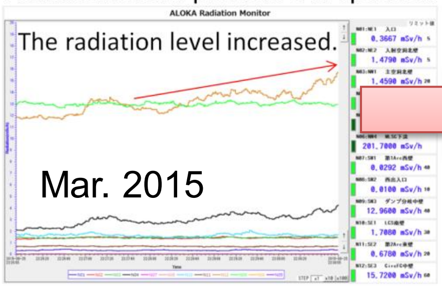
<u>CW operation in Mar. 2016</u>

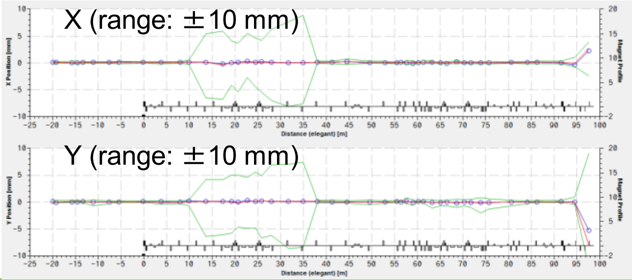
Beam repetition rate：162.5 MHz

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

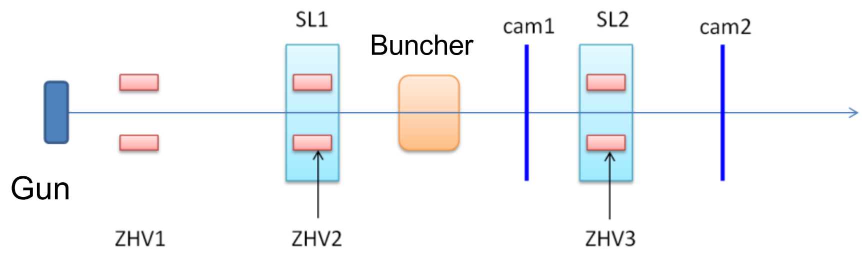
Result

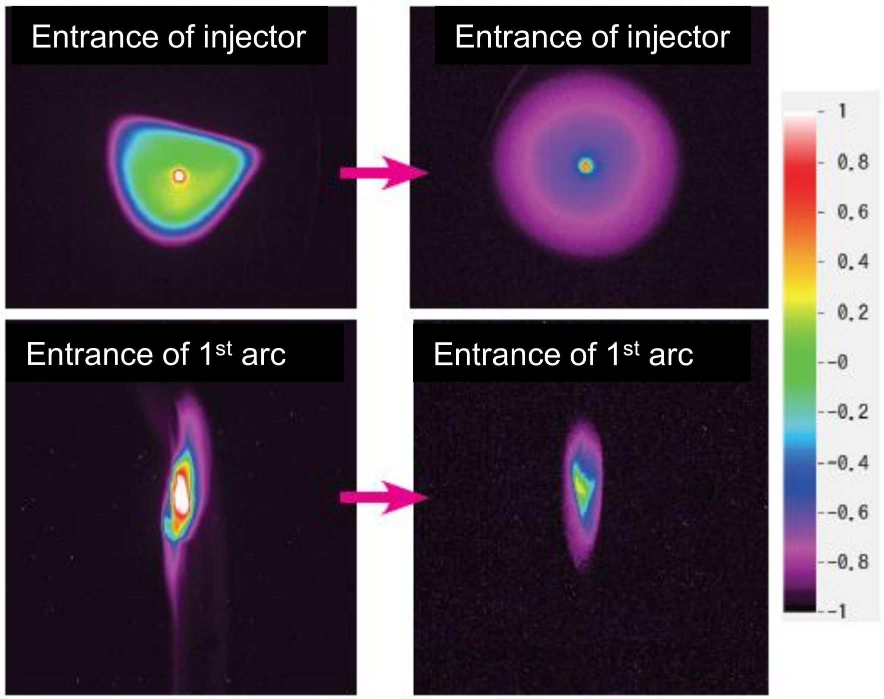
⇒ In the CW operation, the radiation level was low and very stable. Exchange mirror was effective.

Asymmetry of beam profile after DC gun

- In the previous operation, we found that large steering field in the solenoid magnet distorted the transverse profile for the bunch charge of 7.7 pC.

New orbit tuning : We allowed the remaining orbit error inside the solenoid (about 1 mm), and decreased the steering field.





Previous method (Apr. 2014)

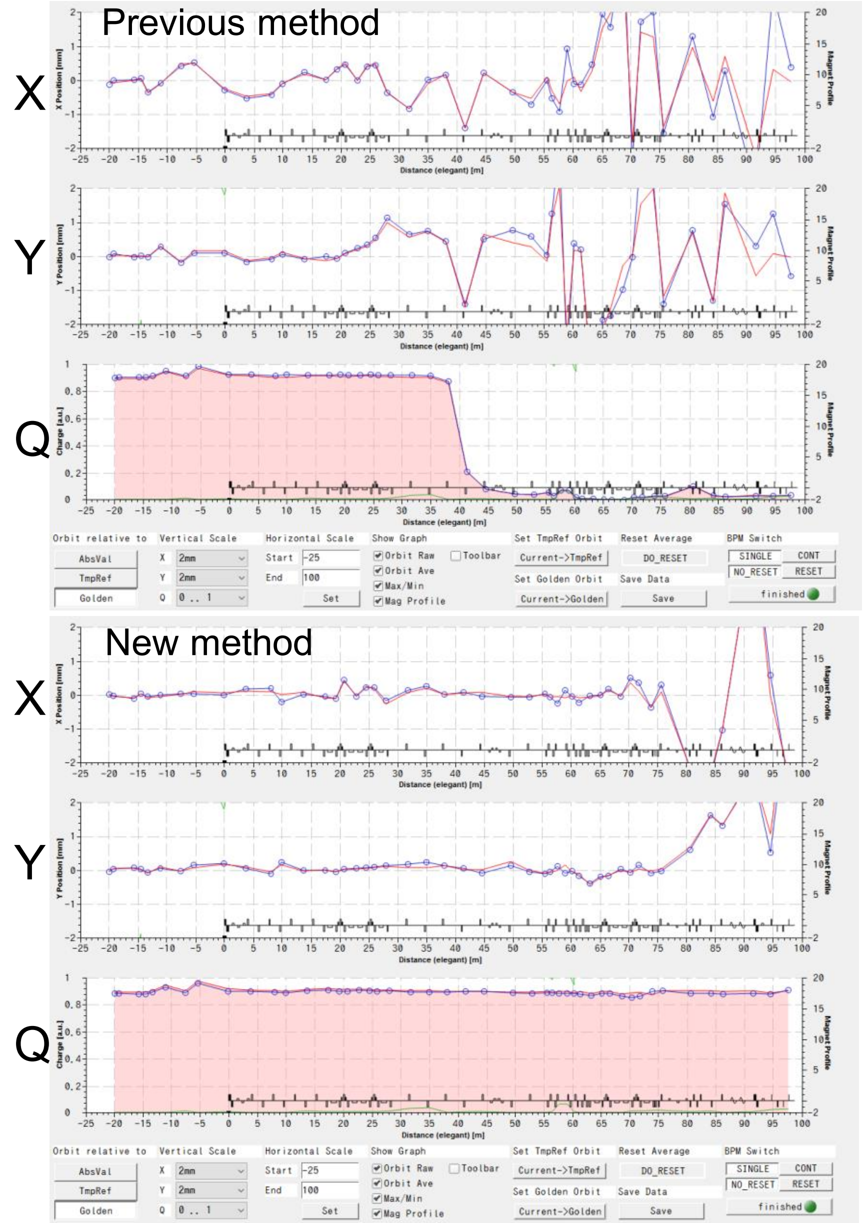
New method (Mar. 2016)

- Result of new method
  - Low energy section : We keep the cylindrical symmetry of the profile.
  - Arc section : The profile distortion decrease.

  ⇒ We decreased beam loss and emittance growth.

Improvement of beam orbit tuning

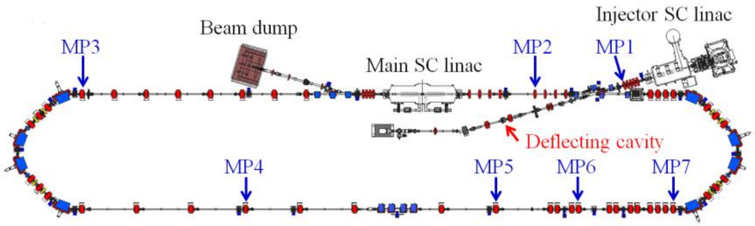
- Previous method：BBA using screen monitor (Measuring the orbit response, when Q field is varying.)
  - Total correction time: - 1 hour
- New method： using BPM and measured response matrix for steering magnet.
- Result
  - Remaining orbit offset: < 0.2 mm (maximum offset: 0.5 mm)
  - Correction time: 1 section, 1 min (total 9 sections)



> - The accuracy and reproducibility improved.
> - Time for orbit tuning was shortened.
> - Total correction time: 1 hour ⇒ 10 min

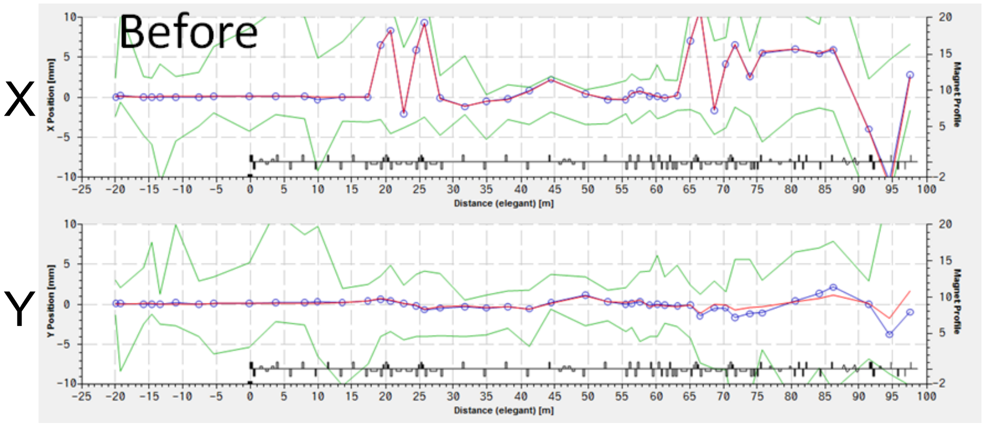
Improvement of beam optics tuning

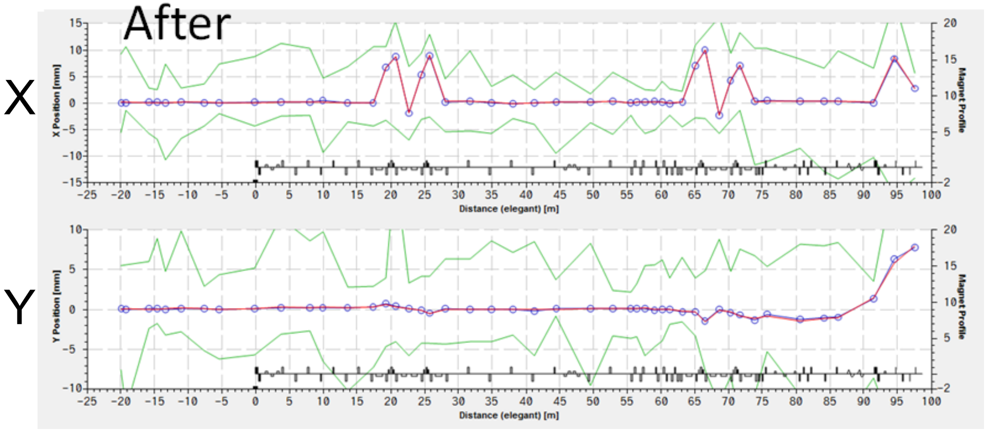
- Previous method: manual tuning…, the reproducibility was not good…
  - In the south long straight section, the achromatic condition was not satisfied…



- New method : The correction values were calculated by measured response matrix about quadrupoles and skew-quadrupoles in the arc section. .

Horizontal and vertical dispersion functions





- The measured dispersion function is almost the same as the design.
- The beam profiles in the 2nd arc improved.
- The beam loss in the 2nd arc decreased.
- Correction time: 10 min

Result of 5.5 pC, 0.9 mA CW operation

Previous operation

CW operation with 0.5 Cp (Jun. 2015)

Improvements

Feb. – Mar. 2016

Orbit stability in CW operation :
In CW operation, orbit distortion and beam loss gradually increased.

We exchanged laser mirrors made of glass for metal mirrors.
⇒ To avoid charge-up
⇒ We achieved stable CW operation

Asymmetry of beam profile after the DC photocathode gun : For 7.7 pC operation, the cylindrical symmetry of transverse beam profile was broken.

New orbit correction method
⇒ Beam profile in low energy improved.

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

New standardize method of magnet
New orbit correction method using BPM
⇒ Reproducibility improved.
⇒ Shortening beam tuning time.

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

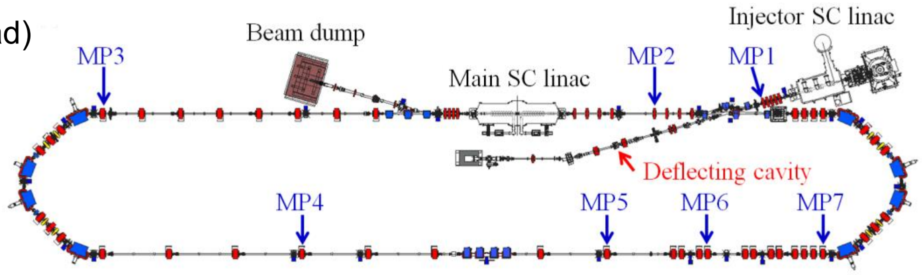
New dispersion correction method
Installing skew quadrupole magnets
⇒ Beam optics was well controlled.
⇒ Beam loss reduced.

History of emittance measurement

Previous emittance measurement result（Q-scan method）

Very low charge (< 0.05 pC/bunch) enx / eny (mm mrad)

	Before main linac	After main linac	After 1st arc	LCS
2014/6/13	0.15 / 0.14	0.14 / 0.12	0.14 / 0.14	0.13 / 0.15
2015/2/17	-/-	-/-	0.25 / 0.25	-/-
2015/2/19	-/-	-/-	-/-	0.17 / 0.19



Middle charge (0.5 pC/bunch)

2015/3/25	-/-	-/-	0.32 / 0.28	0.41 / 0.30

High charge (7.7 pC/bunch)

2014/6/19	-/-	-/-	42 / 15	-/-
2014/6/20	-/-	2.9 / 2.4	5.8 / 4.6	-/-
2015/6/15	-/-	1.9 / 2.4	4.5 / 4.5	-/-

⇨ After the 1st arc section, emittance increased.

Upper column : enx (mm mrad)
Lower column : eny (mm mrad)

Emittance measurement in 2016（Q-scan method）

Charge	Before main linac	After main linac	South straight
5.3 pC	1.0 0.66	2.7±0.21 1.0±0.071	
7.7 pC	- 0.9	1.8±0.40 1.02±0.33	1.5±0.082 1.1±0.058

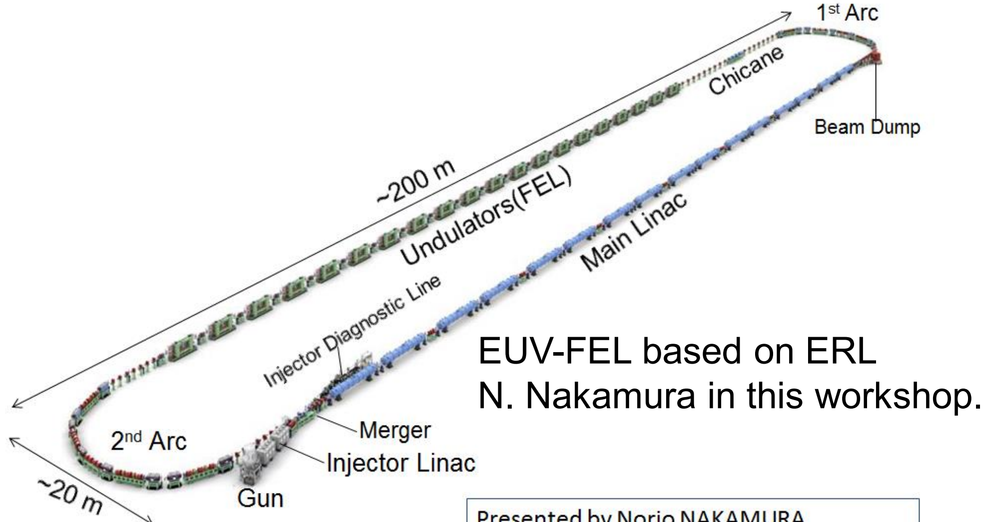
We reduced the emittance growth for 7.7 pC operation. However, to achieve design emittance (0.45 mm mrad), we required more operation time.

60 pC bunch charge, non-ERL operation in March 2017

60 pC bunch charge, non-ERL operation

- As the next topic of the beam experiment for the cERL, we have planned to increase the bunch charge toward the development of CW-FEL accelerator based on a superconducting linac, since it requires higher bunch charge and higher peak current.
- For example, EUV-FEL accelerator based on ERL for future lithography light source requires the bunch charge of 60 pC, and CW-XFEL accelerator like the LCLC-II requires the bunch charge of 300 pC.
- In March 2017, we have planned beam operation to demonstrate generation, acceleration and transportation of the bunch charge of 60 pC without energy recovery.

- <u>Condition of beam operation</u>
  - Maximum bunch charge: 60 pC (Target for EUV-FEL)
  - Injector total energy: 2.9 MeV for energy recovery ⇒ 5.1 MeV (without energy recovery) to reduce space charge effect

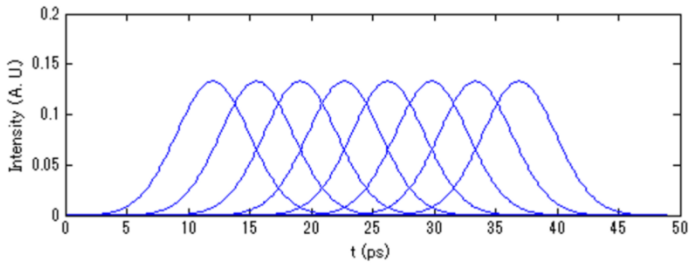


Presented by Norio NAKAMURA
ERL2015 (https://www.bnl.gov/erl2015/)

Generation of Higher Bunch Charge

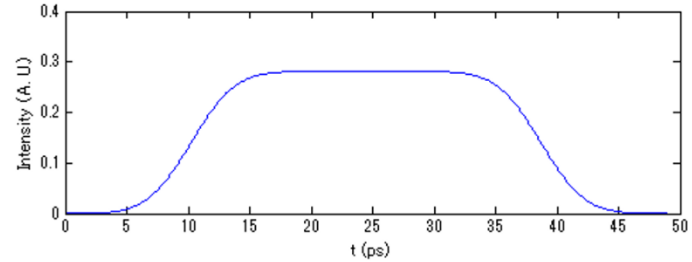
We measured the generated bunch charge from a GaAs photocathode by a Faraday cup, which located at 1 m from the cathode.

- Quantum efficiency (QE): 3 %



Laser pulse: single Gaussian 3 ps RMS

- We achieved the generation of 60 pC bunch charge.

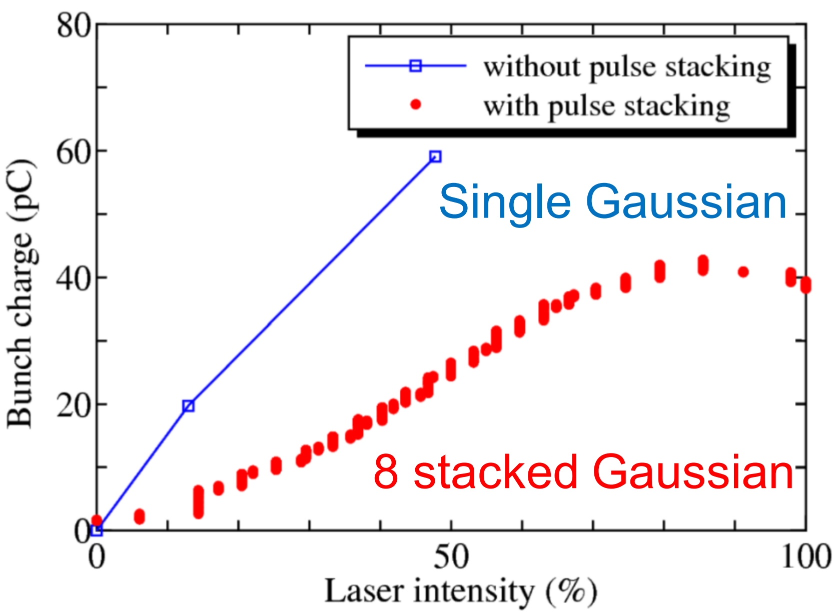


For emittance compensation, we extend the pulse length of the excitation laser.

Laser pulse: 8 stacked Gaussian 31 ps FWHM

- The maximum bunch charge was limited to 40 pC.
- The crystals to stack the laser pulse decrease the irradiated laser power on the cathode.
- The stacked laser power is about 1/3 of the original power.

⇒ We did the beam operation with 40 pC bunch charge.



Bunch length measurement in injector diagnostic line

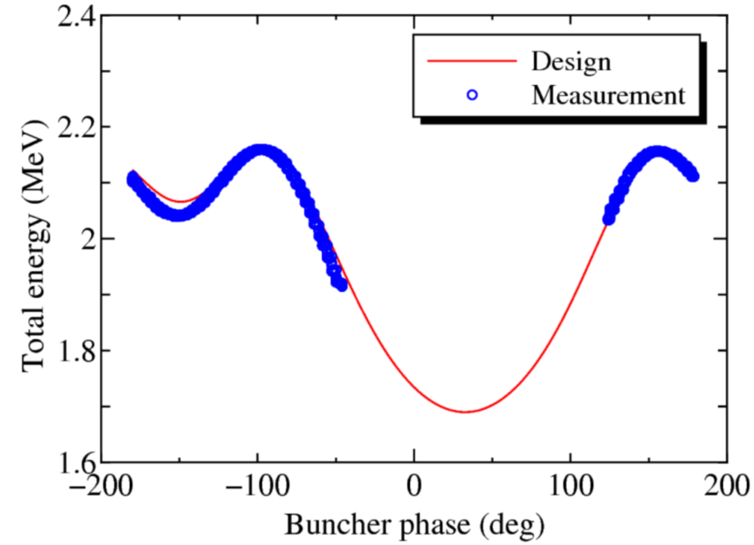
In this operation, we improved phase tuning method for RF cavities.

<u>Pervious phase tuning method (- Mar. 2016)</u>

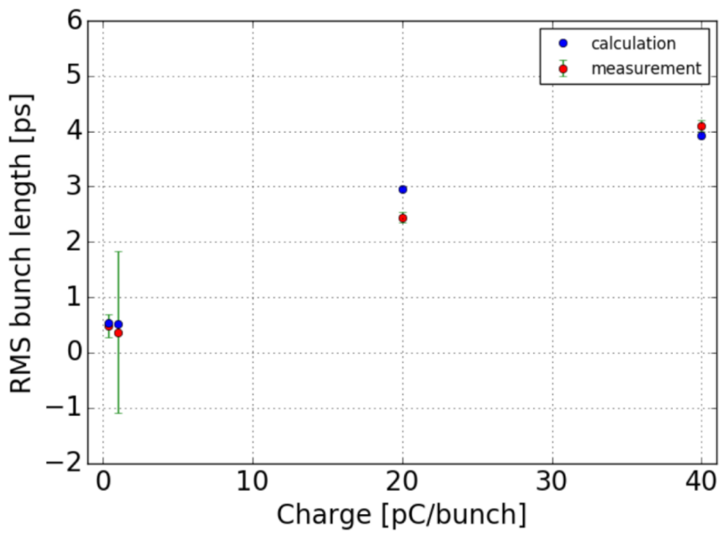
⇒ The agreement of the longitudinal dynamics between measurement and model was not so good, because this method is not the same as phase tuning method in the optics design simulation.

<u>New phase tuning method (Mar. 2017-)</u>

⇒ The results of the bunch length measurement gave good agreement with the values that had been obtained by model simulation.

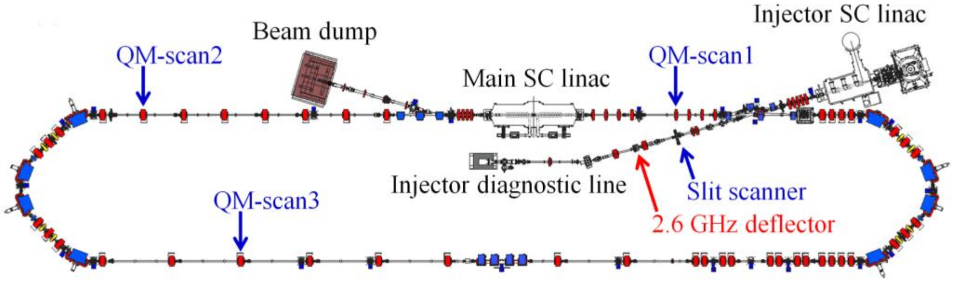


Designed and measured responses of accelerated beam energy to buncher phase. In the measurement, the beam was accelerated by the buncher cavity and the first injector cavity. The phase of the first injector cavity was fixed to maximum acceleration phase. The beam energy was measured by the first bending magnet in merger section.



Emittance measurements in diagnostic line

After optics tuning for the bunch charge of 40 pC, we measured normalized rms emittance by slit-scanner in the injector diagnostic line and Quadrupole scan method.

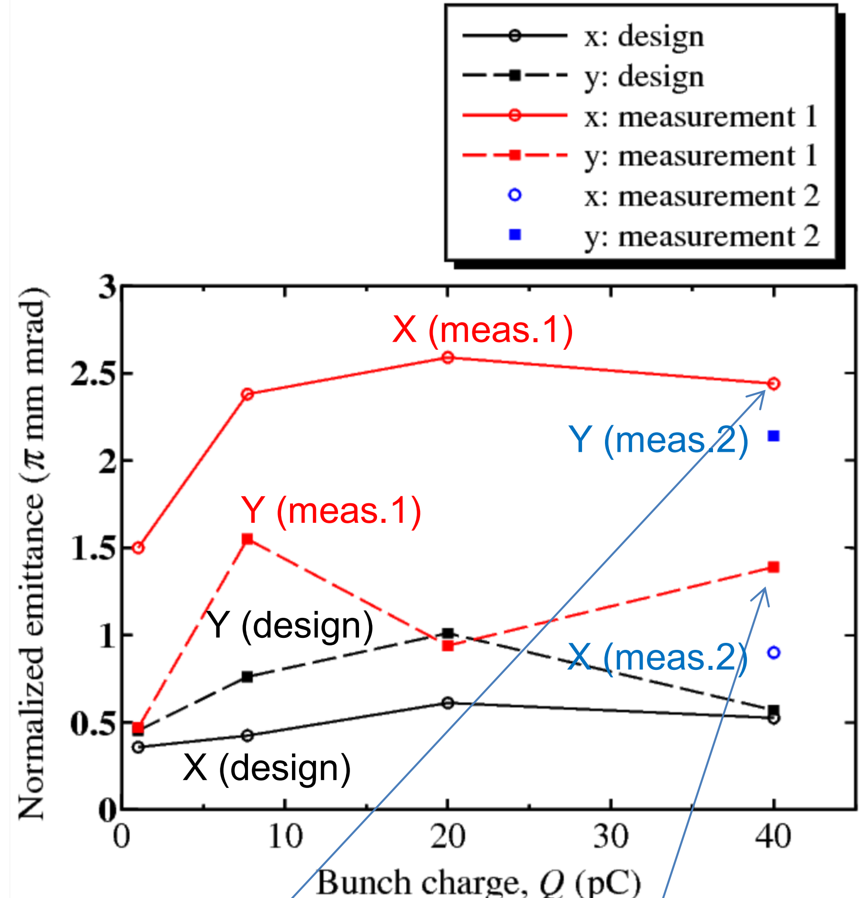


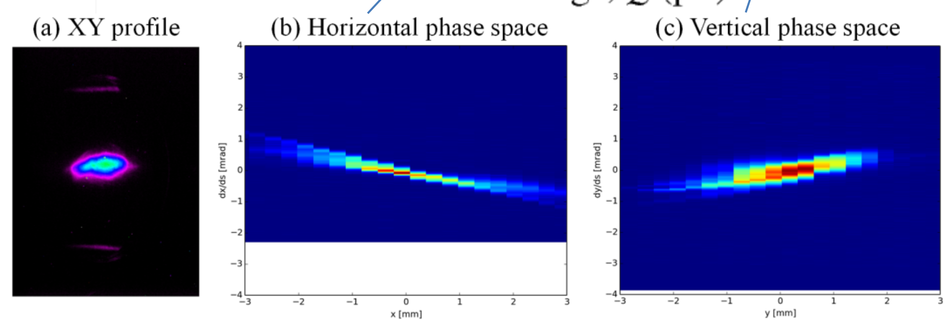
<u>Results by slit-scanner in the injector diagnostic line (Preliminary)</u>

Beam total energy: 5.1 MeV

- We measured emittances in two different transport conditions.
- In measurement 1, the vertical beam size was focused at the slit scanners.
- In measurement 2, the horizontal beam size was focused at the slit scanners.

⇒ So far, we did not achieve the design emittance.





Emittance measurements in recirculation loop

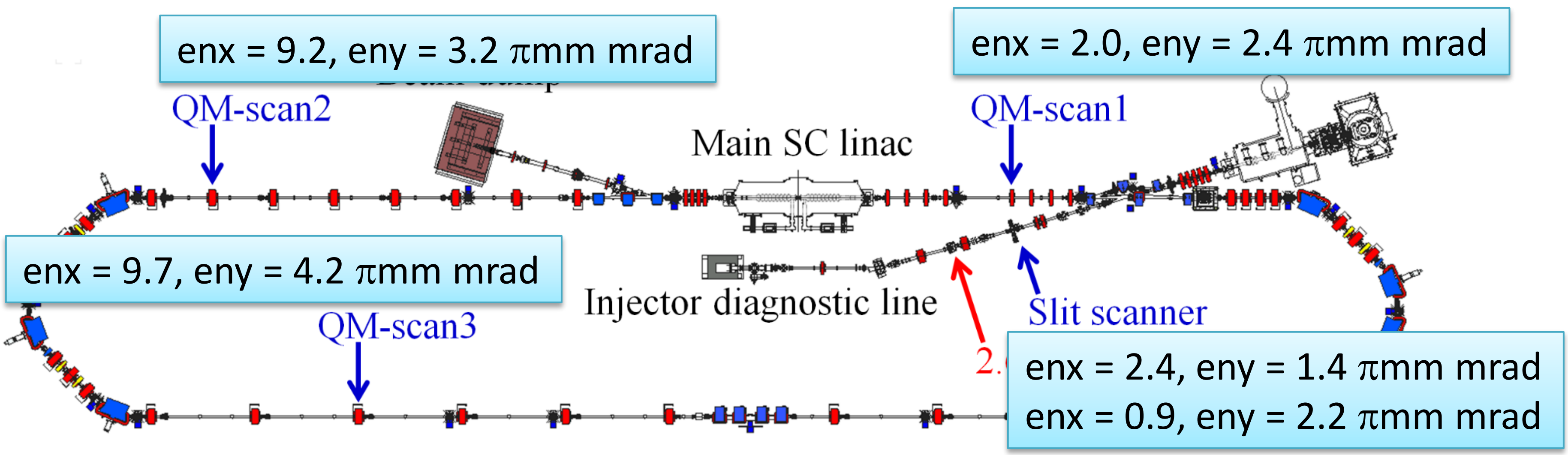
Results by waist-scan method in the recirculation loop (Preliminary)

Beam total energy: 17.1 MeV

For 40 pC bunch charge

- QM-scan1: enx = 2.0, eny = 2.4 πmm mrad
- QM-scan2: enx = 9.2, eny = 3.2 πmm mrad
- QM-scan3: enx = 9.7, eny = 4.2 πmm mrad

⇒ The emittance increases after the merger and the main linac.



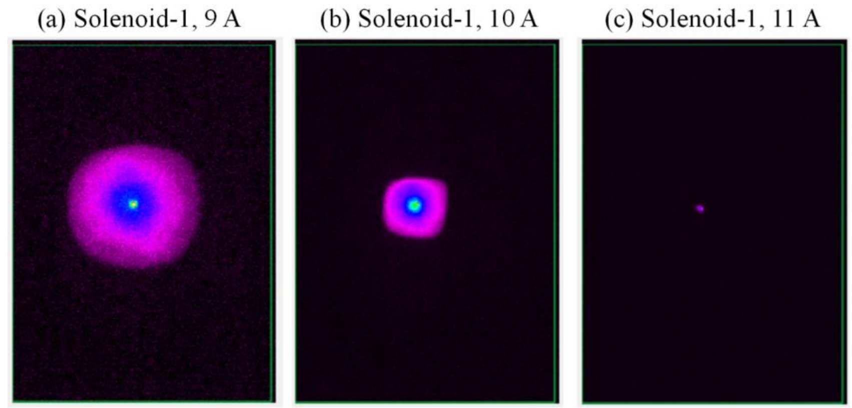
In the recirculation loop, we observed large emittance growth, because the optics in the recirculation loop was not well matched.

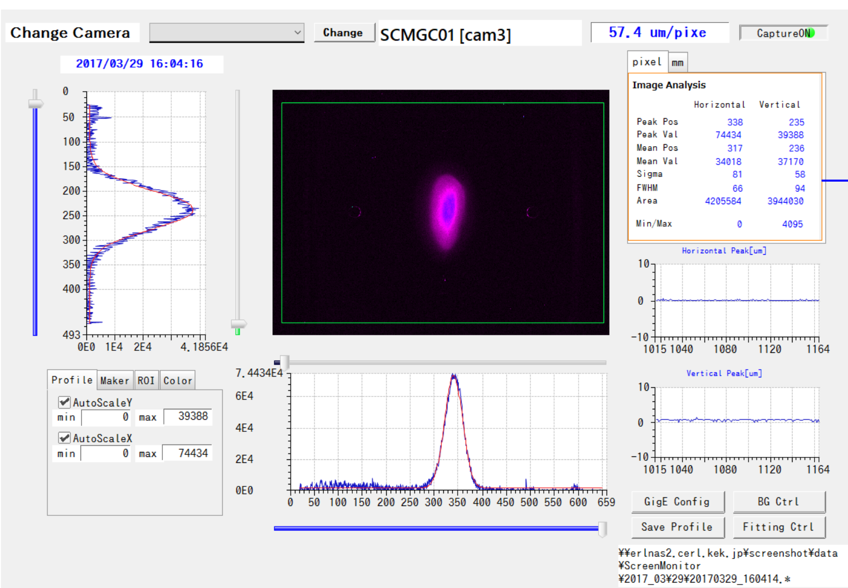
Beam performance in low energy region

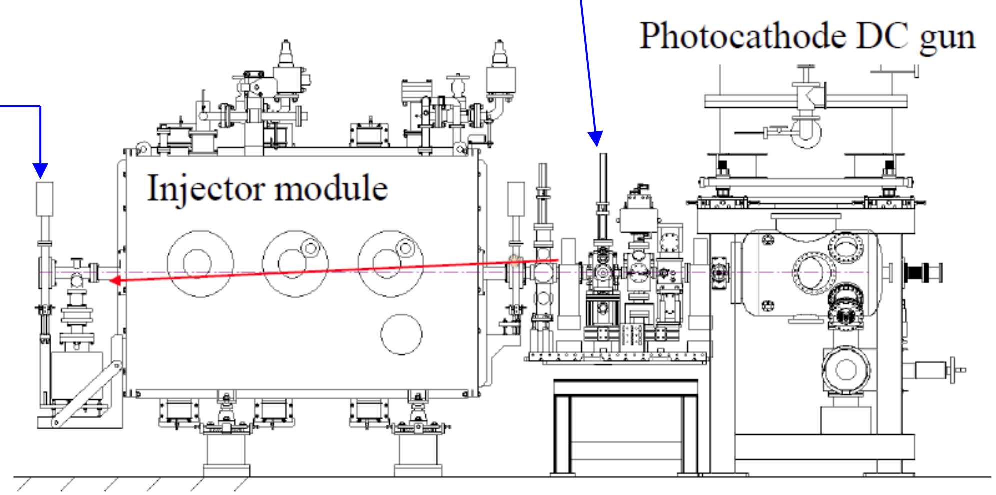
To achieve design emittance, we are studying the source of the emittance growth for 40 pC bunch charge.

- Distortion of transverse profile from cylindrical symmetry before the injector cavities (450 keV)
- Asymmetric transverse profile at the exit of the injector cavities (5.1 MeV)

⇒ In this operation, we carried out single kick response measurements in the low energy region.

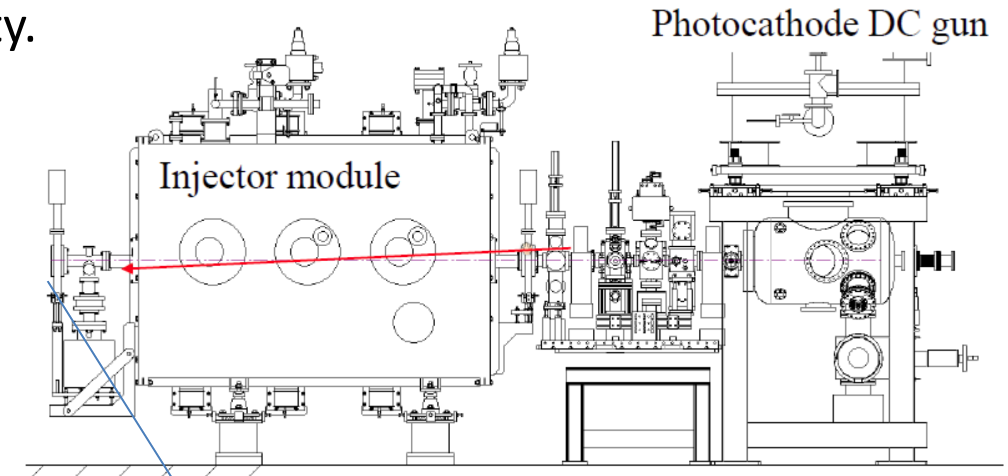






Single kick response for injector 1st 2-cell cavity

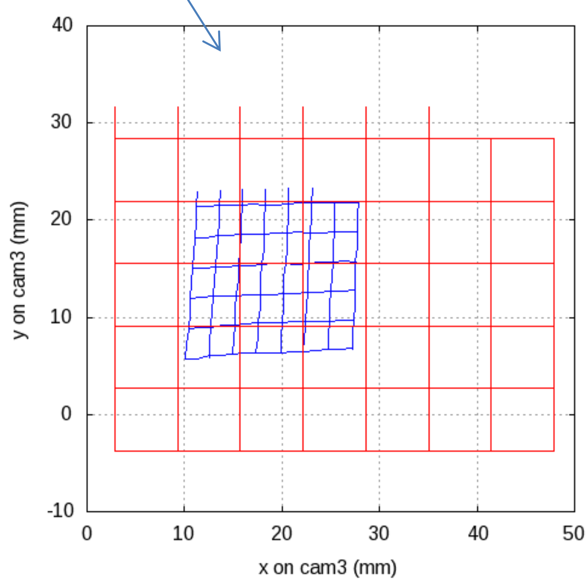
- In order to find the source of the asymmetry profile, we measure the single kick response for injector 1st 2-cell cavity.



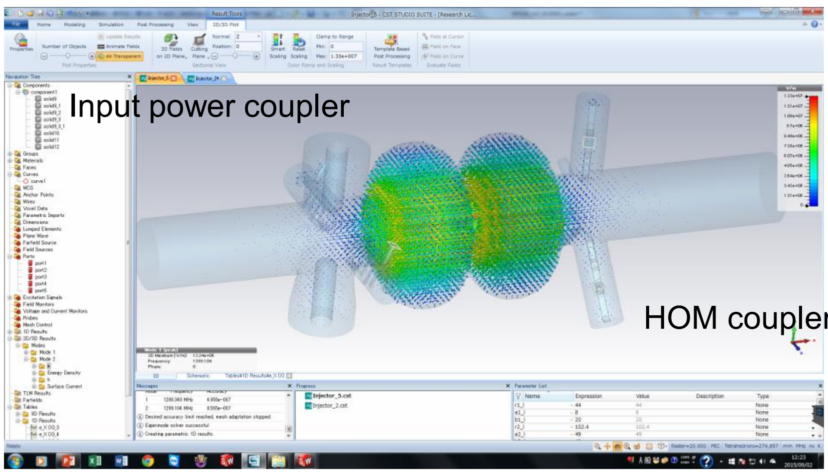
The beam is kicked by horizontal and vertical steering magnets, which are located at the entrance of injector SC linac.

⇒ From the single kick response, we obtained the asymmetric focusing force caused by the injector cavity. The input and HOM coupler may cause the effect.

⇒ Based on the measurement results, we are correcting the model of the injector cavity.



- All the injector cavities are turned off.
- The first injector cavity is turned on, and it is affected by the focusing force caused by the first cavity.



Courtesy of T. Konomi

Summary

Summary

- 5.5 pC bunch charge, 0.9 mA CW ERL operation (March, 2016)
  - We improved orbit tuning and optics correction using new methods.
  - A good prospect is now seen for CW 10 mA operation, because we achieved very low beam loss in 0.9 mA CW operation with same bunch charge for CW 10 mA operation, in Mar. 2016.
- 60 pC bunch charge, non-ERL operation (March, 2017)
  - We achieved generation, acceleration and transportation of 40 pC bunch charge beam, and measured the beam performance.
  - In order to improve the beam performance, we are studying beam dynamics in low energy region.

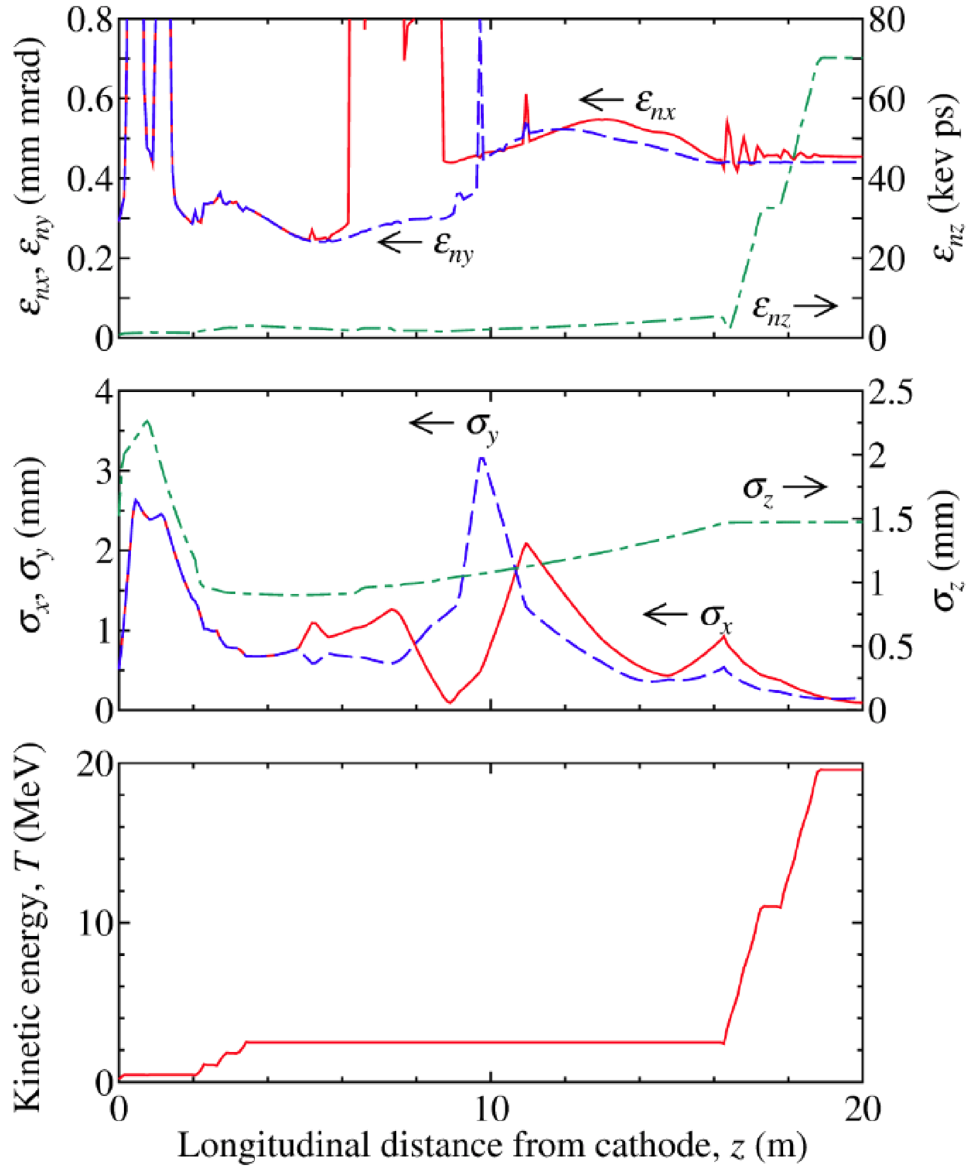
- Outlook
  - We continue the cERL DC gun operation (500 kV) in order to study the low energy beam performance for 60 pC bunch charge.
  - I hope to operate the whole cERL accelerator including superconducting cavities in March 2018 in order to continue 60 pC bunch charge experiment.

Backup slides

Design optics for 7.7 pC bunch charge

- Initial condition
  - Laser diameter : d = 1.5 mm
  - Laser pulse : 8 stacked 3 ps gaussian

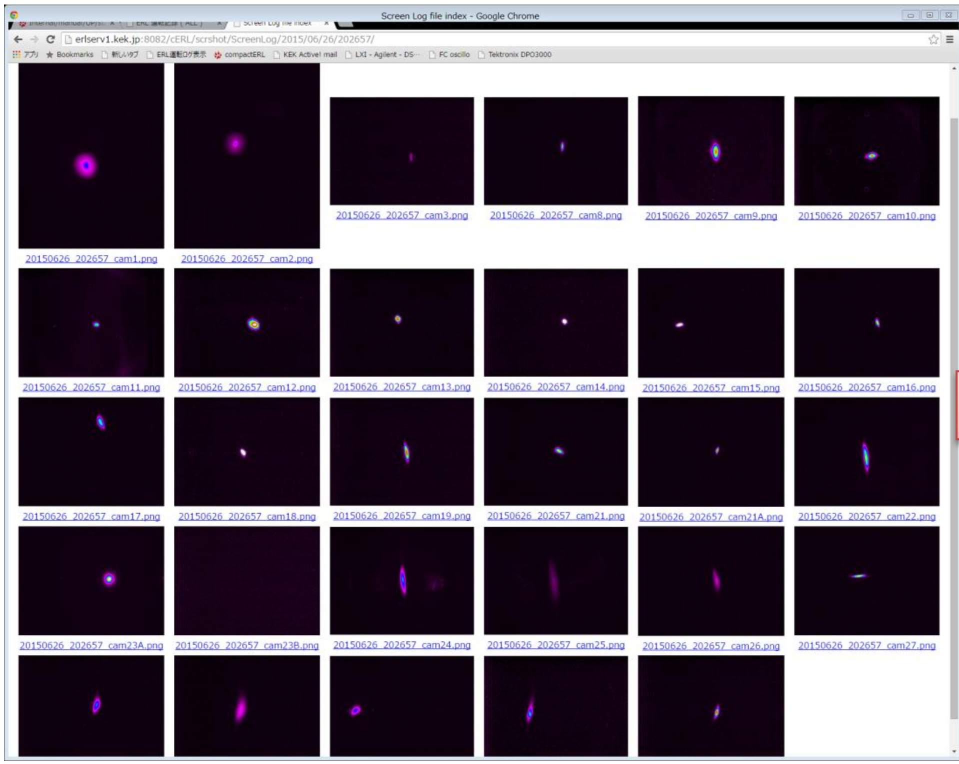
- Beam parameters at the exit main linac
  - enx = 0.45 mm mrad
  - eny = 0.44 mm mrad
  - stdz = 1.47 mm (4.9 ps)



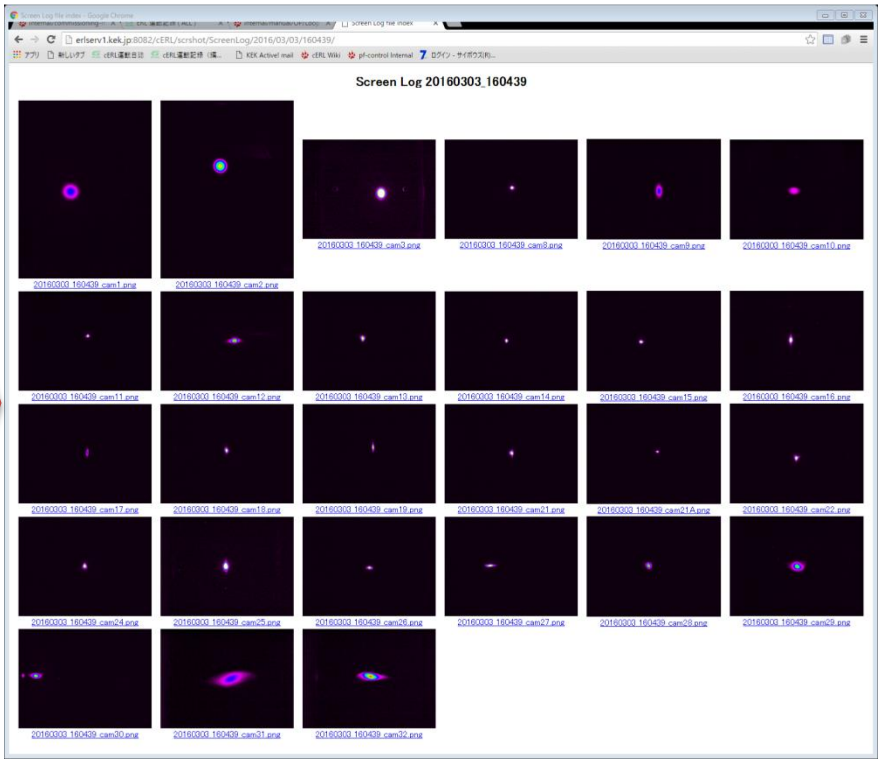
Beam profiles in 0.5 pC operation

- After fine beam tuning, the beam profiles are the almost same as the design beam sizes.
- We succeeded to reduce the beam loss in the recirculation loop.

Previous operation (26 Jun. 2015)



3 Mar. 2016



Design optics for 40 pC bunch charge