Injector Development at KEK

16:00-16:30, September 19, 2019
Workshop on Energy Recovery Linacs (ERL2019)
Helmholtz-Zentrum Berlin

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On behalf of cERL team

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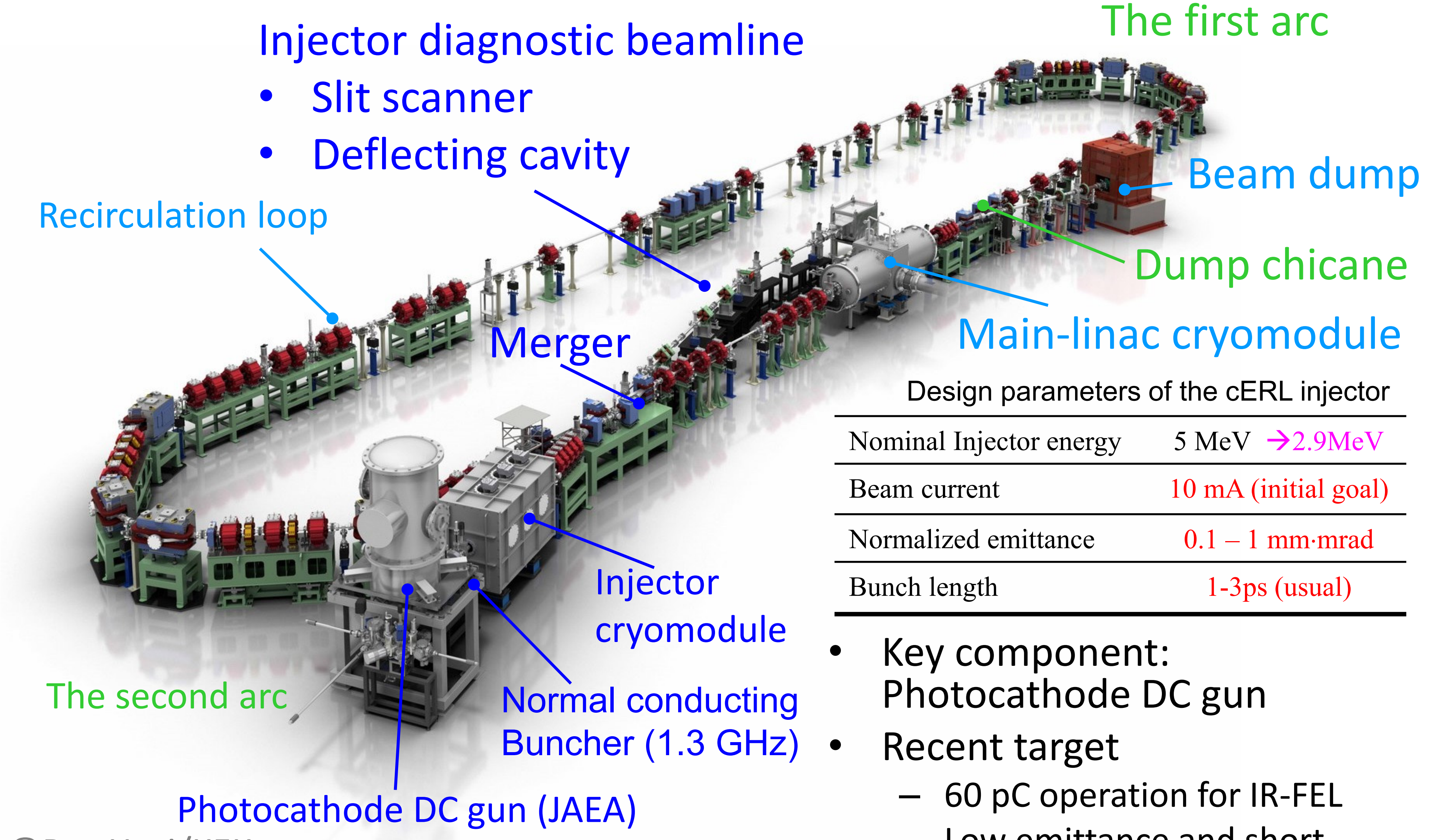
加速器研究施設
Accelerator Laboratory

Outline

- Injector for cERL at KEK
  - Key component: Photocathode DC gun
  - To generate low emittance and short bunch beam
- DC gun operation
  - Stable operation with 500 kV
- Development of beam quality in cERL injector
  - History of beam quality development
  - Next target: 60 pC operation for IR-FEL
- Summary

Injector of compact ERL at KEK



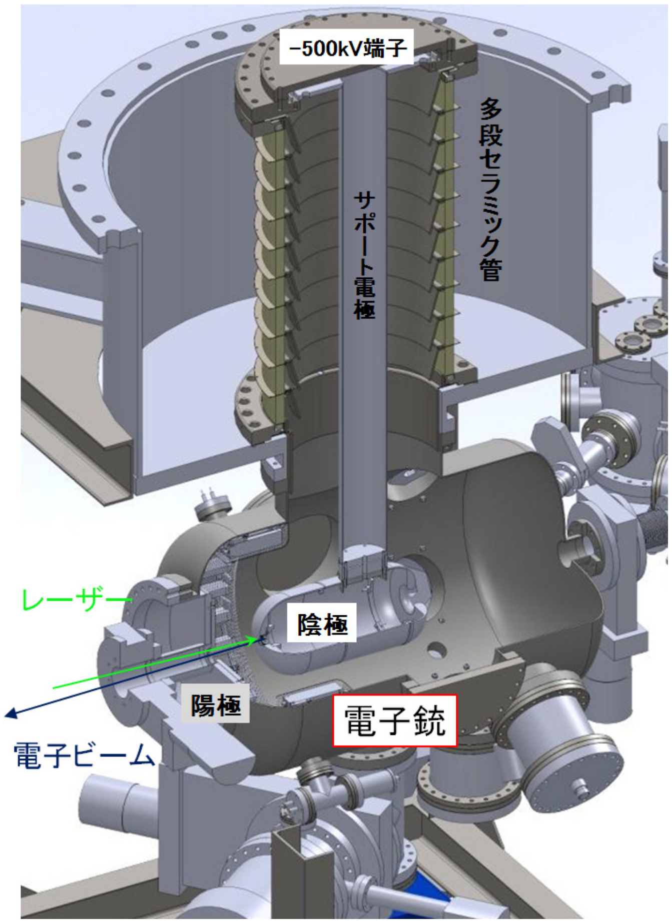
Design parameters of the cERL injector

Nominal Injector energy	5 MeV →2.9MeV
Beam current	10 mA (initial goal)
Normalized emittance	0.1 – 1 mm·mrad
Bunch length	1-3ps (usual)

- Key component: Photocathode DC gun
- Recent target
  - 60 pC operation for IR-FEL
  - Low emittance and short electron bunch

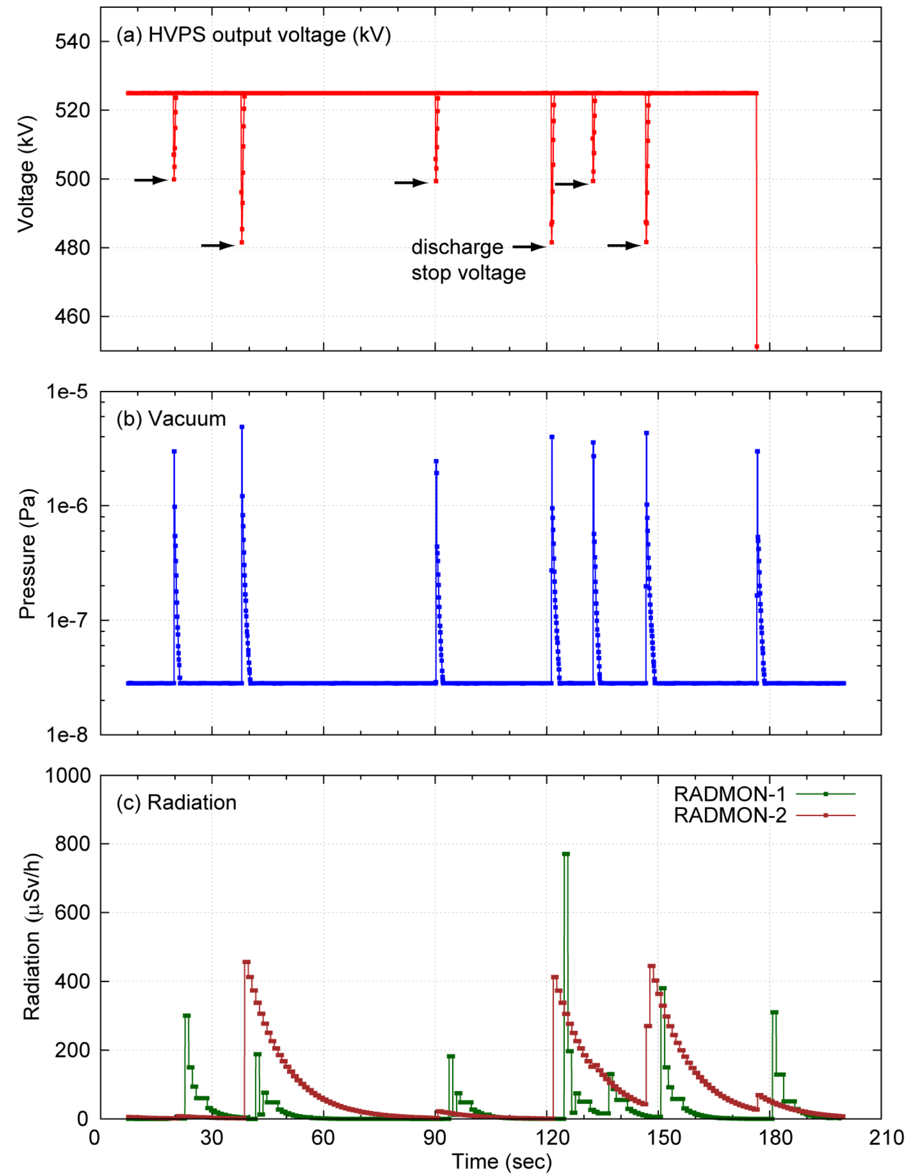
Status of KEK-cERL Photocathode DC Gun

Keyword: Discharge stop voltage



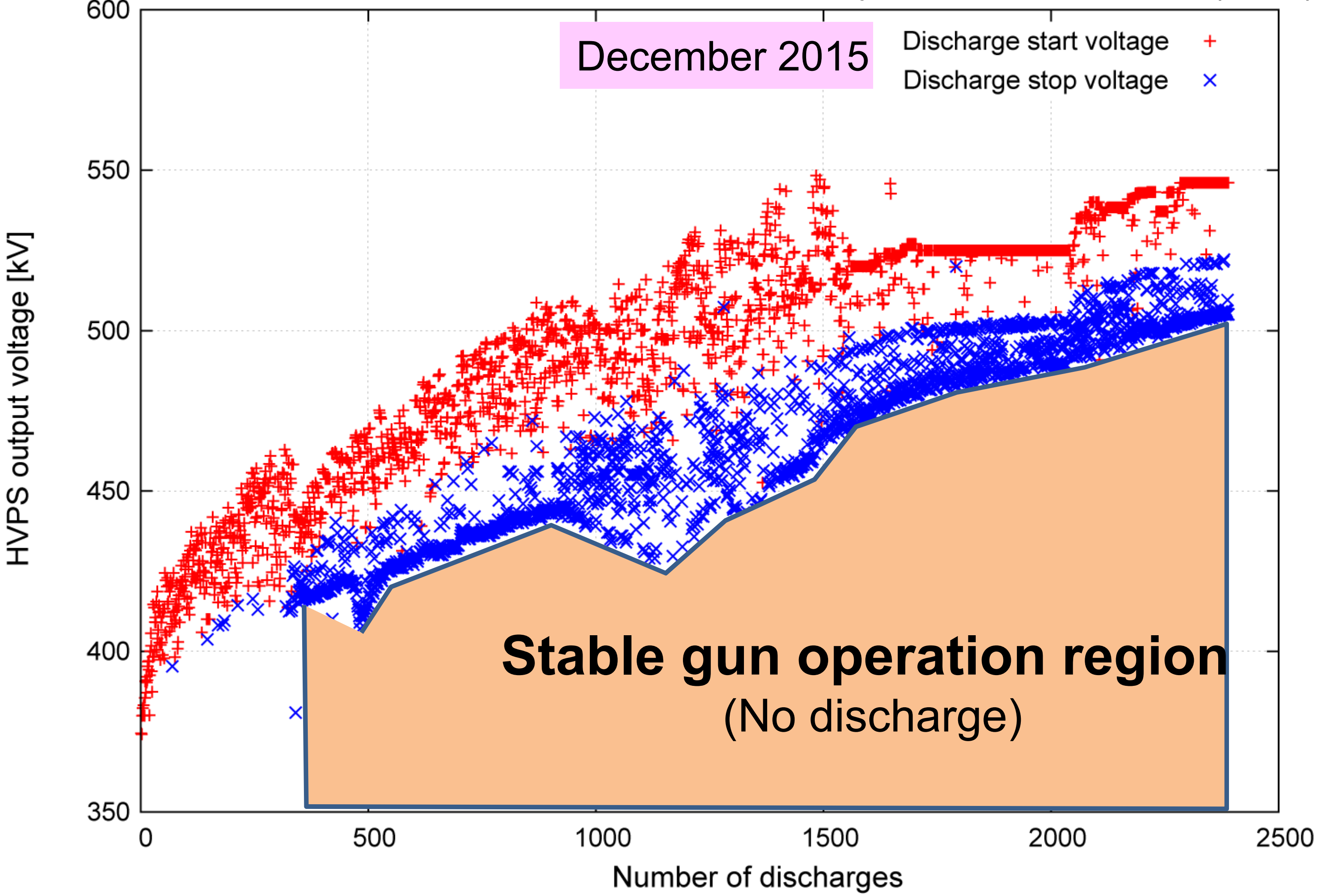
Records the event where the discharge stops and recovers during conditioning. The voltage at which discharge stops is defined as the discharge stop voltage.

Cathode: Bulk GaAs cathode



HV Conditioning History in Dec. 2015

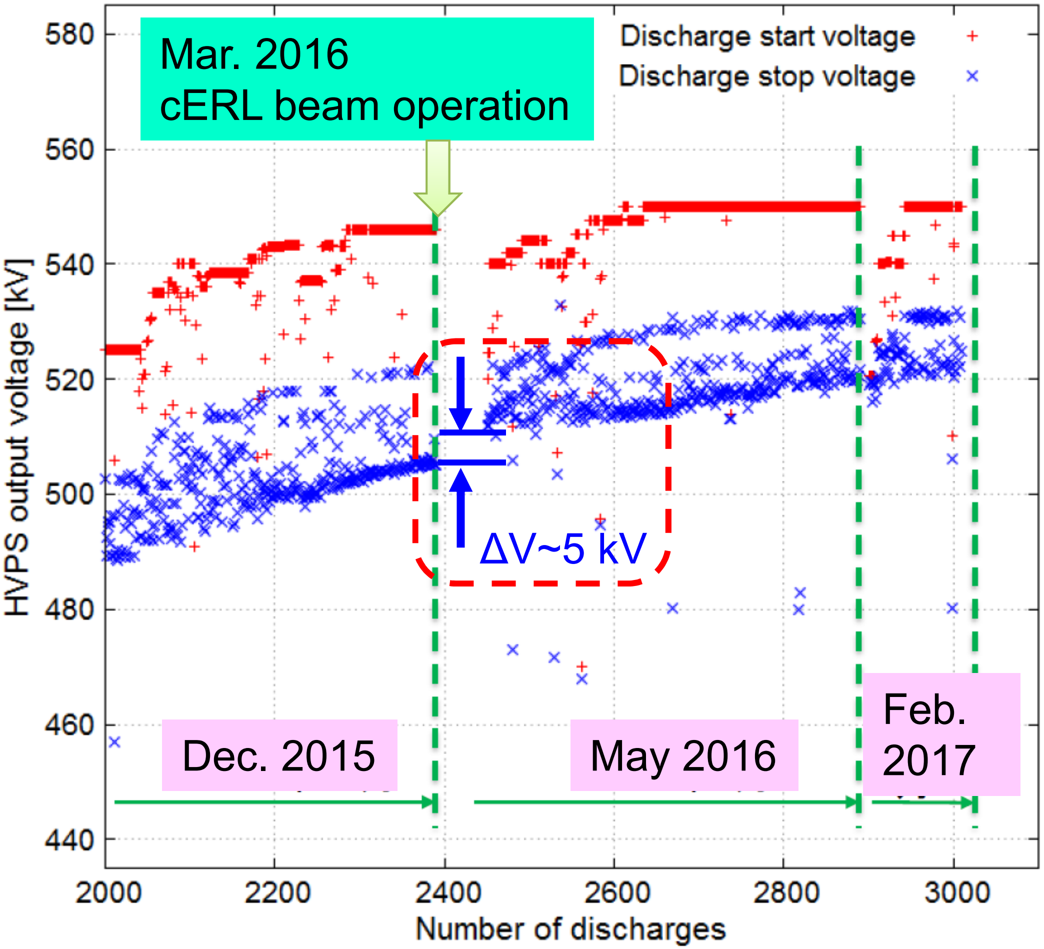
M. Yamamoto and N. Nishimori, Appl. Phys. Lett. 109, 014103 (2016)



Discharge does not occur at all below the minimum discharge stop voltage.

HV Conditioning History

by *courtesy* of M. Yamamoto



Two additional conditionings have been done after December 2015.

<u>cERL beam operation was carried out in March 2016.</u>

・The electron gun acceleration voltage is mainly 390 kV.

・No discharge during operation.

<u>Conditioning in May 2016</u>

・Discharge stop voltage rose about 5 kV in the initial stage.

・Conditioning to a discharge stop voltage of approximately 520 kV.

<u>Conditioning in February 2017</u>

・The history at the end of conditioning in May 2016 is retained.

・No cERL beam operation during this period.

The long-term stable operation of the electron gun itself has the same effect as HV conditioning.

Duration of the 500 kV Gun Stable Operation

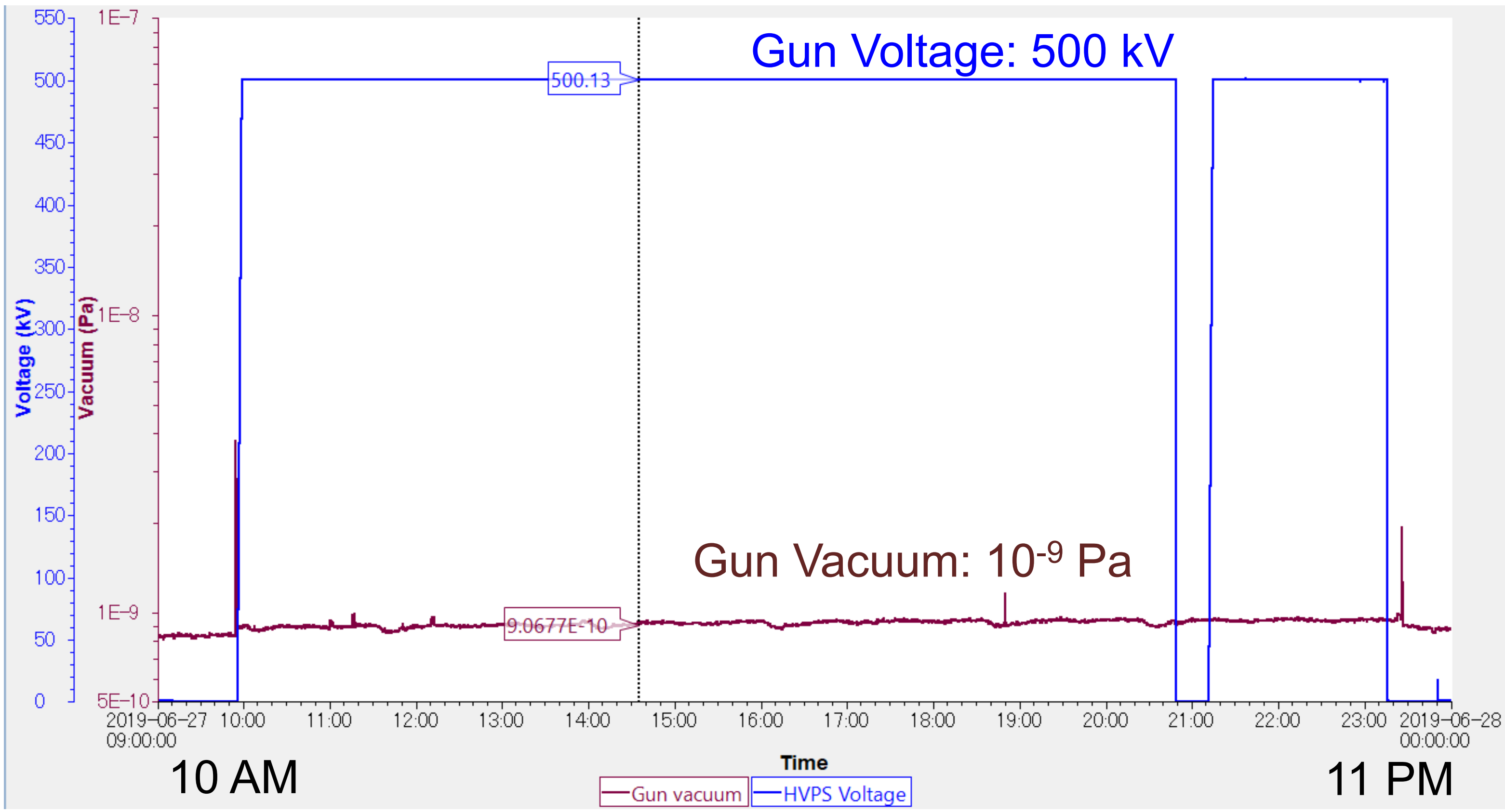
by *courtesy* of M. Yamamoto

500 kV operation ▪Until June 2018 : 369 hrs.

▪April 2019 : 169 hrs. June 2019 : 187 hrs.

Total : 725 hrs.

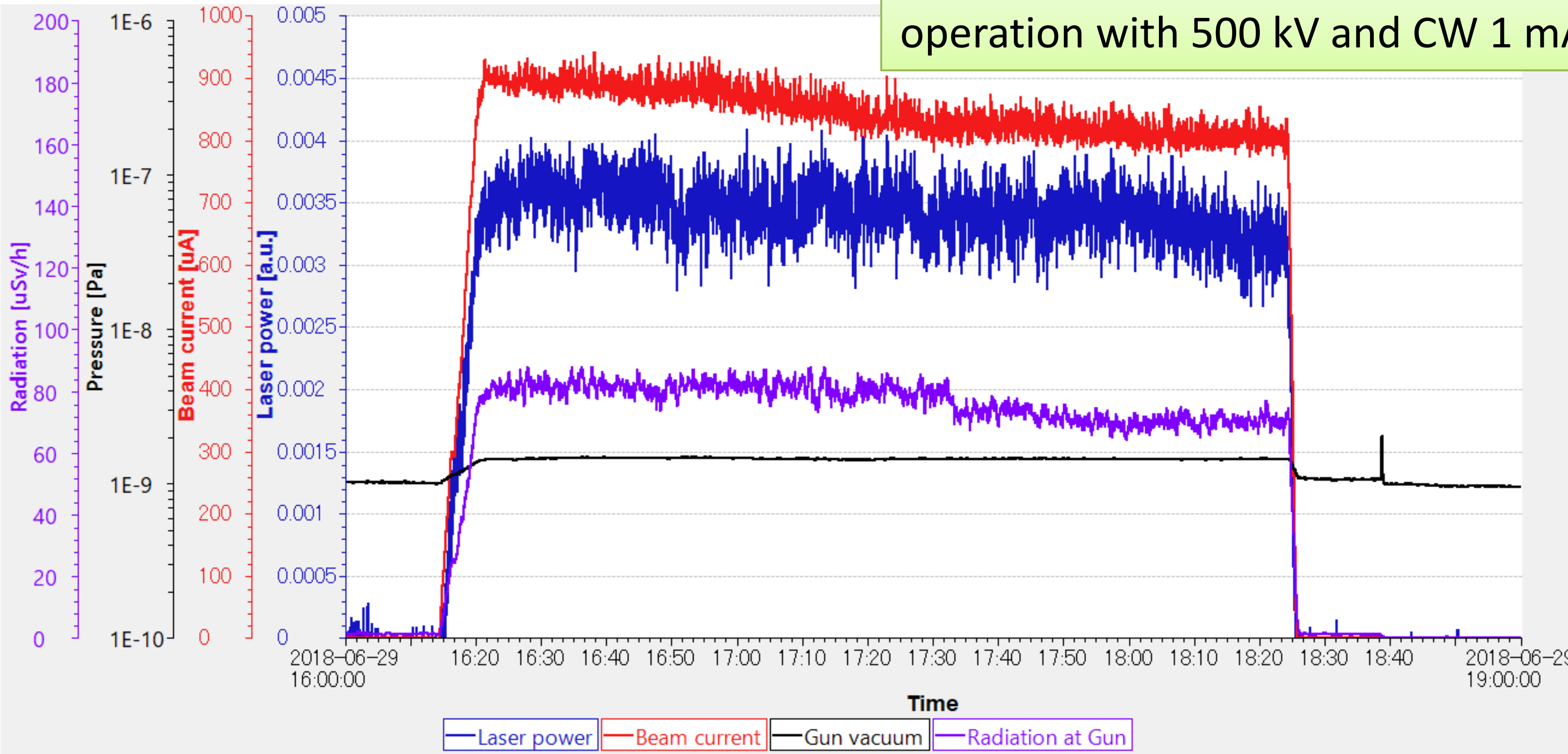
Typical daily history of DC-gun vacuum & voltage during cERL operation



500kV & ~ 1mA CW beam operation

by *courtesy* of M. Yamamoto

World record: Stable DC photocathode gun operation with 500 kV and CW 1 mA



- DC-gun voltage : 500 kV, Beam current : 800-900 μA,
  Cathode : Bulk-GaAs
- CW operation keep for about 2 hours. There are no trips.
- Observe changes in beam current due to QE drop. (4.0% -> 3.2%)

N. Nishimori, et al., “Operational experience of a 500 kV photoemission gun”, Phys. Rev. Accel. Beams 22,053402 (2019).

Development of beam quality in cERL injector

- Since 2013, we operates cERL injector to check hardware performance and beam quality.
- How about is the achieved beam quality?
  - Up to 7.7 pC bnch charge, we achieved designed performance.

- Next target
  - Beam commissioning with 60 pC for IR-FEL operation

- Since March 2017, we continue high bunch charge operation (40 – 60 pC) to develop beam handling method toward high average current FEL.
- Important things of injector:
  - Not for achieving peak performance in the injector
  - For generating and transporting appropriate beam at the undulator for IR-FEL

- How about is the beam performance in the previous operations (until June 2018) ?

Result of the commissioning at Injector part (@the end of June/2018)

Parameter	Achieved performance	Target values	Remark
Beam energy T	5.6 MeV (typ.), 5.9 MeV (max.)	5 MeV (typical)	OK
DC voltage for DC gun V_{gun}	500 kV in operation	500 kV	OK
Acceleration Energy E_{acc}	7 MV/m (typ.)		OK
Normalized Emittance (Very low bunch charge)	≈ 0.07 μm·rad (@~10 fC/bunch, T=390 keV)	0.1 μm·rad	OK
Normalized Emittance (Low bunch charge)	≈ 0.17 μm·rad (@0.02 pC/bunch, T=5.6 MeV)	0.1 μm·rad	OK
Normalized Emittance (Medium bunch charge)	≈ 0.8 μm·rad (@7.7 pC/bunch, T=5.6 MeV)	≤ 1 μm·rad (at the beginning) 0.1 μm·rad (aggressive)	OK Still
Normalized Emittance (High bunch charge)	2~3 (@60 pC/bunch)	1 μm·rad	Not bud
Momentum spread $(\sigma_p/p)_{rms}$	$< 10^{-3}$ (< 1 pC/bunch) $(1.5 - 2.5)\times10^{-3}$ (@7.7 pC/bunch)	$\leq 10^{-4}$ (3 GeV ERL)	Should be OK
Jitter of momentum $(\Delta p/p)_{rms}$	6×10^{-5}	$\leq 10^{-4}$ (3 GeV ERL)	OK
Bunch length σ_t	~ 2 ps (@1.5 pC) ~ 7 ps (@7.7 pC)	2 ps (typical)	Not bad

For 60 pC, the beam performance was not bad, but did not reach the design. Therefore, we have to improve injector beam performance toward design parameters.

Injector operation for IR-FEL test in June 2019

- Required beam performance at the undulator
  - Bunch charge: 60 pC
  - Normalized RMS emittance: $< 3\ \pi$ mm mrad
  - RMS bunch length: < 250 fs

- Target beam performance for injector
  - Normalized RMS emittance: $< 3\ \pi$ mm mrad
  - RMS bunch length at the exit of Main Linac: 2 – 4 ps (The bunch is compressed in the first arc section.)

- In June 2019, we operated the cERL to improve beam performance for 60 pC bunch charge.

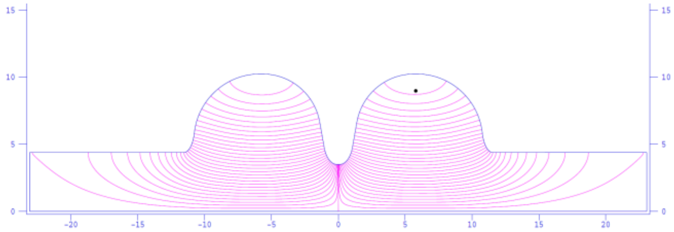
- Plan of IR-FEL test in cERL
  - October 2019, beam operation for 60 pC beam tuning and bunch compression (continued)
  - Nov. 2019 to Feb. 2020, Installation of an undulator for IR-FEL test
  - March 2020, beam operation for IR-FEL test (Goal: to generate and observe IR-FEL)

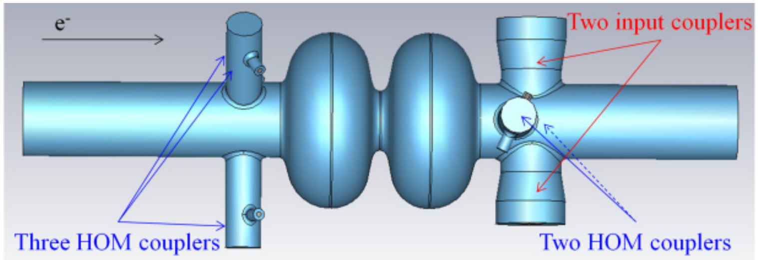
Improvement of injector model

- To design injector optics, we use GPT (General Particle Tracer).
- However, previous injector model was not so good for high bunch charge.

Injector cavity model

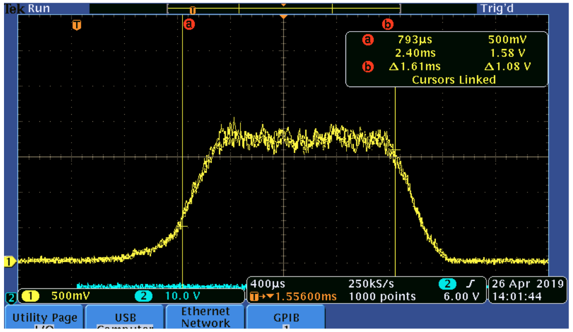
- 2D model (Poisson/Superfish) ⇒ 3D model with input and HOM couplers (CST)

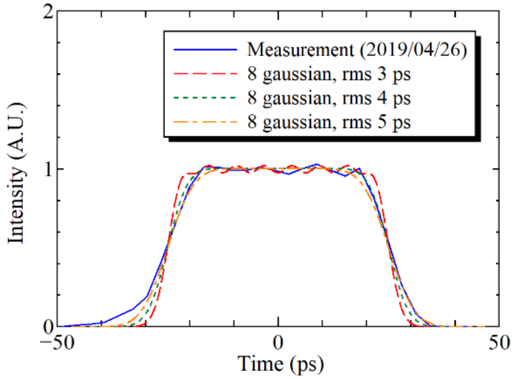




Laser distribution for photocathode

- Uniform circular transverse distribution ⇒ Measured transverse distribution
- Flat top temporal distribution ⇒ Measured temporal distribution



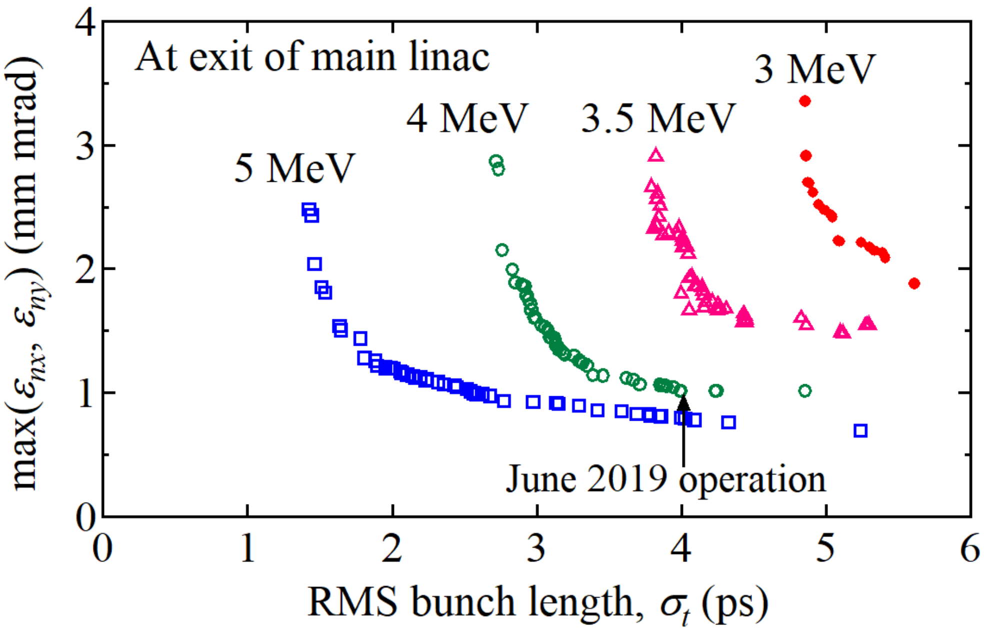


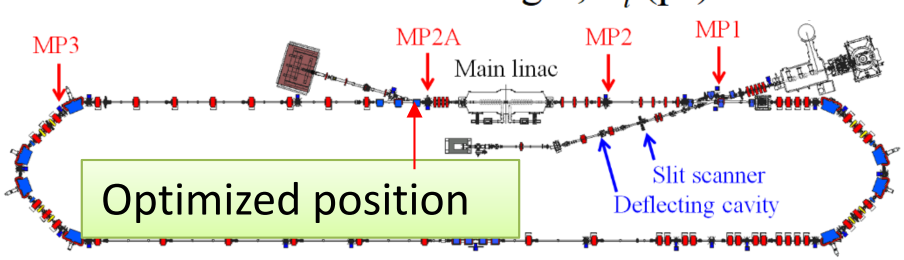
Quadrupole magnet model

- Hard edge model (GPT original) ⇒ New model with fringe field.

Injector energy and beam quality

- Higher injection energy is effective to improve injector beam performance.
- However, the injector energy is restricted by SRF cavity performance and energy ratio between injector and recirculation for ERL operation.
- We investigated the relation between injector energy and beam quality.





Injector optimization: GPT + MOGA

For 5 MeV, the beam quality is good. However, recirculation operation is difficult for 5 MeV.

We selected an optimized parameters with
- 4 MeV injector energy
- 4 ps RMS bunch length

for high charge operation in June 2019.

For 4 MeV injector energy, we can do energy recovery operation.

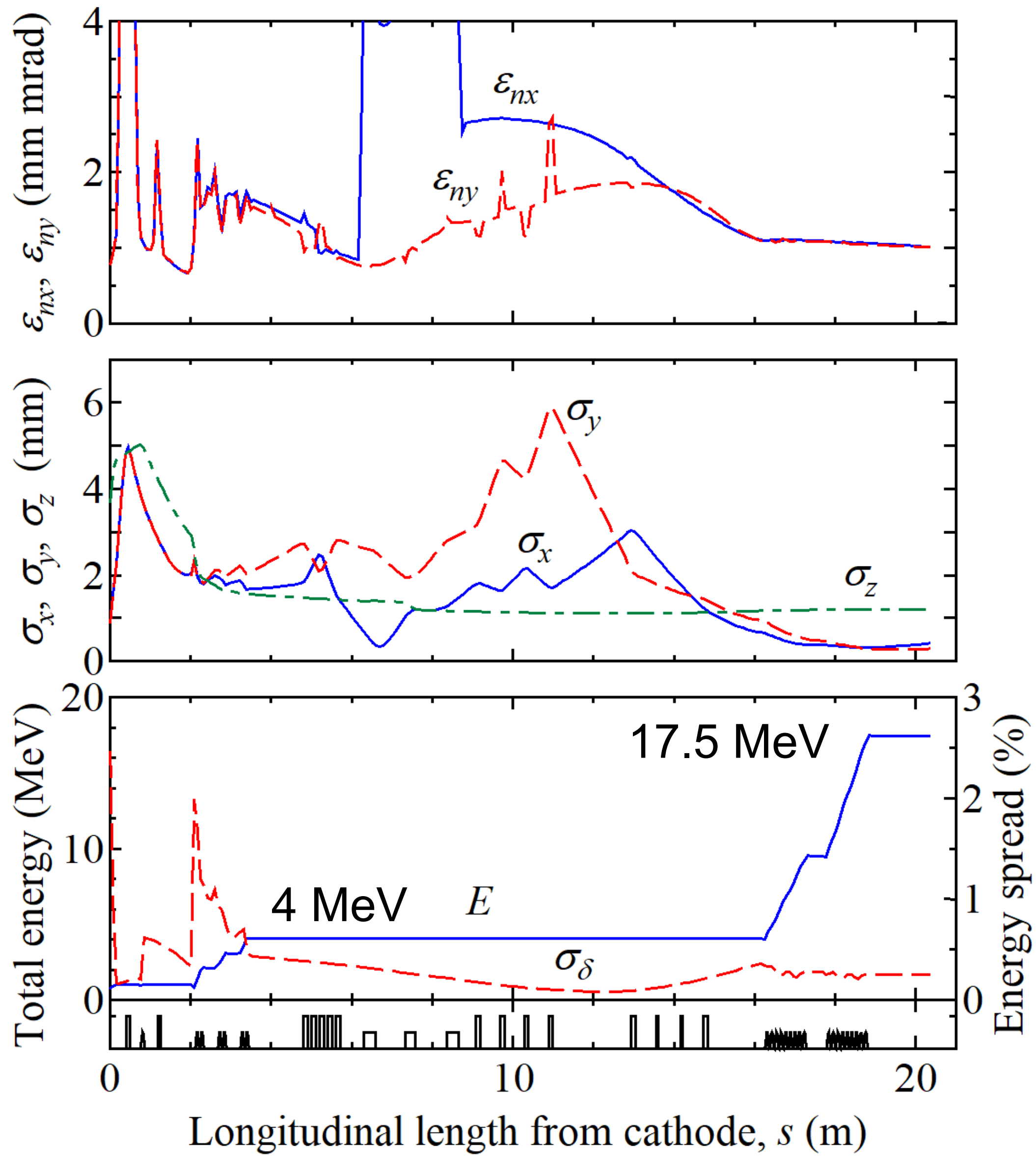
Injector optics design with 4 MeV and 4 ps

Operation parameters in June 2019

- Injector: 4 MeV
- Recirculation: 17.5 MeV
- Target beam performance at the exit of Main Linac
  - Normalized rms emitance ε_{nx}, ε_{ny} : 1.0, 1.0 π mm mrad
  - RMS bunch length : 4 ps
  - α_x = -1.25
  - α_y = -0.357
  - β_x = 5.87 m
  - β_y = 2.83 m

Goal in June 2019 operation:

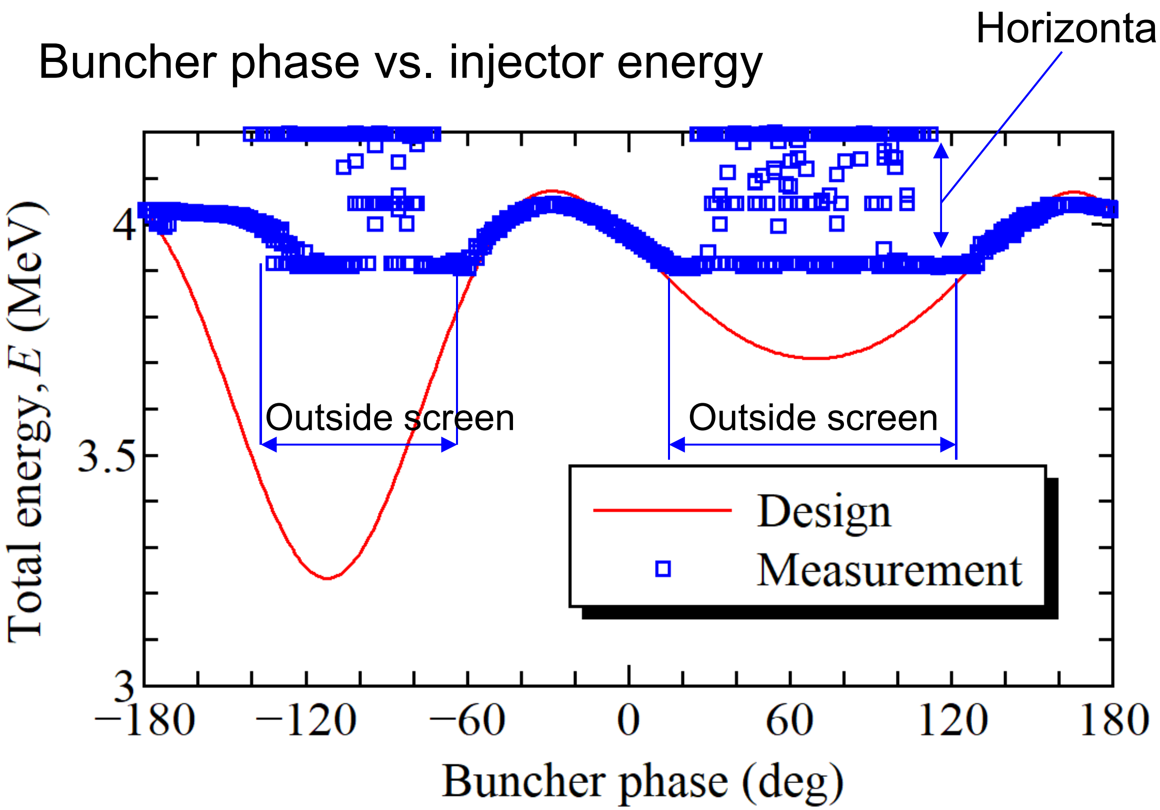
- To transport 60 pC beam with the designed performance.
- To compare the designed performance and measured results.



Injector tuning with low bunch charge

- To adjust a single particle motion without space charge effect, we operated the injector with 1 pC bunch charge.
  - To adjust beam trajectory in the injector cavity and the merger section
  - To adjust beam energy and acceleration phase for buncher and injector cavities

Buncher phase vs. injector energy



In order to adjust longitudinal dynamics, we measured energy response to buncher phase.

The beam energy was measured on the screen in the merger section.

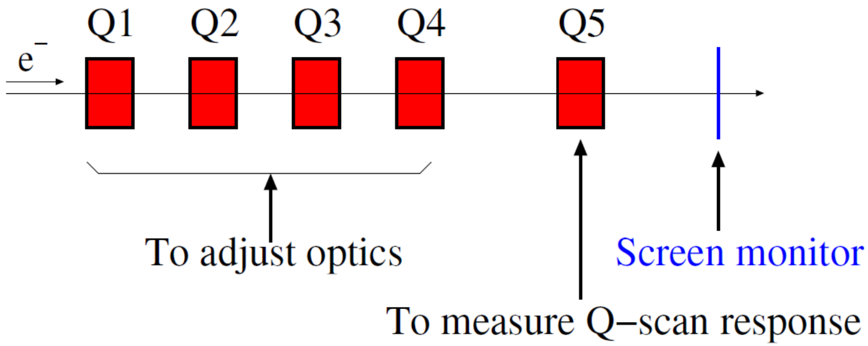
After fine accelerator voltage and phase tunings, the measured response was almost consistent with the design response.

Injector tuning with 60 pC

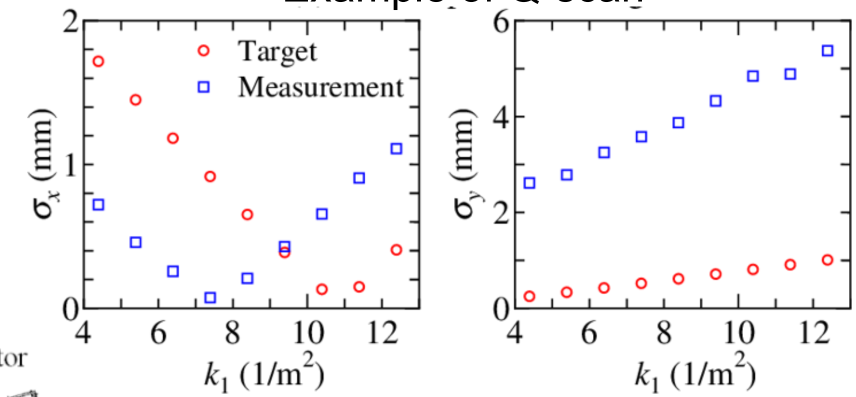
- To adjust multi particle motion including space charge effect, we measured quadrupole-scan (Q-scan) response.

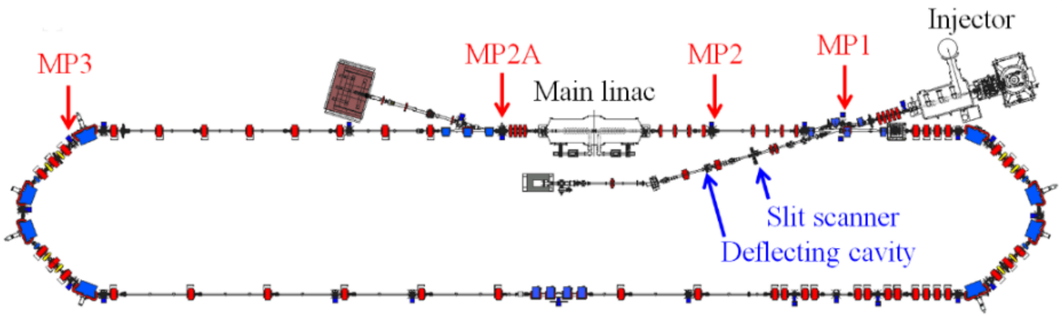
<u>Procedure of optics matching</u>

1. Calculate a target quadrupole response from the design optics.
2. Measure the Q-scan response, and calculate the difference between the target and measured responses.
3. Measure a response matrix about the Q-scan response, when we individually vary the other four quadrupole magnets.
4. Calculate the correction values for the four quadrupole magnet by solving the inverse measured response matrix.



Example of Q-scan



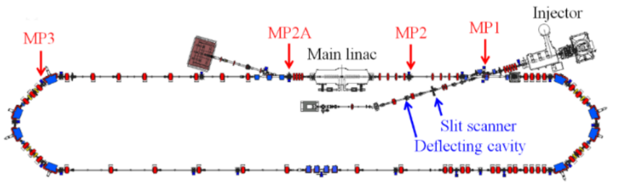


Optics matching points

- For injector: MP1, MP2, MP2A
- For first arc: MP3

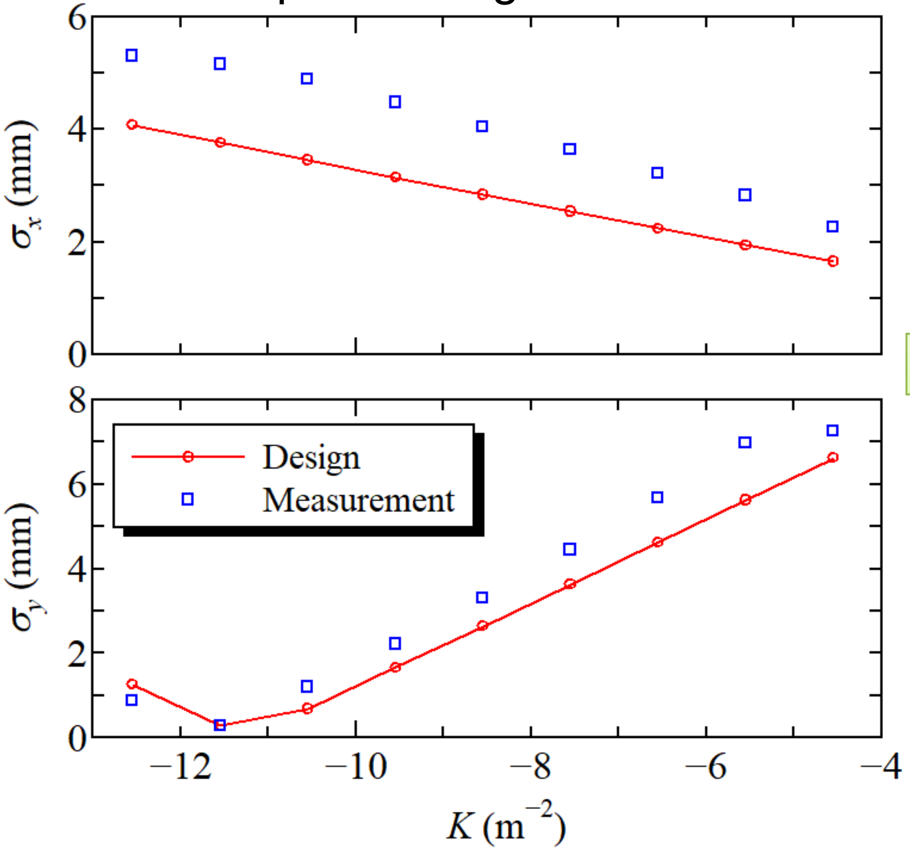
Result of optics tuning

- In previous 60 pC operation in June 2018, the difference of response still remained after optics tuning.
- In 2019, we succeeded optics tuning with 60 pC.

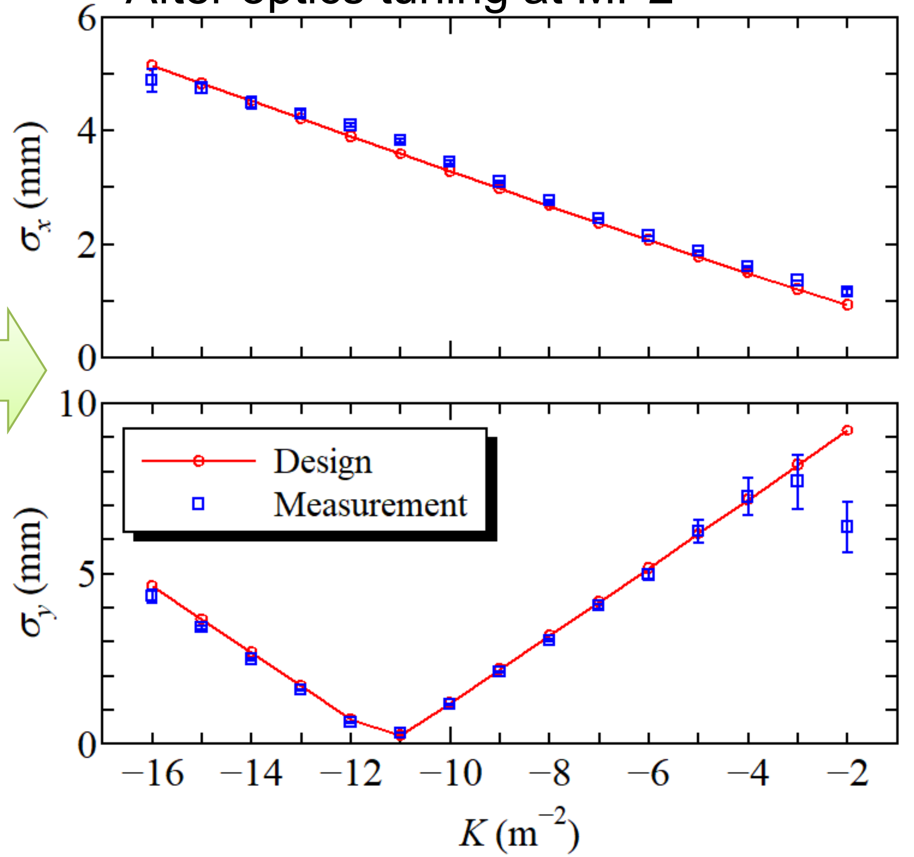


MP2: matching point at the entrance of ML

Before optics tuning at MP2



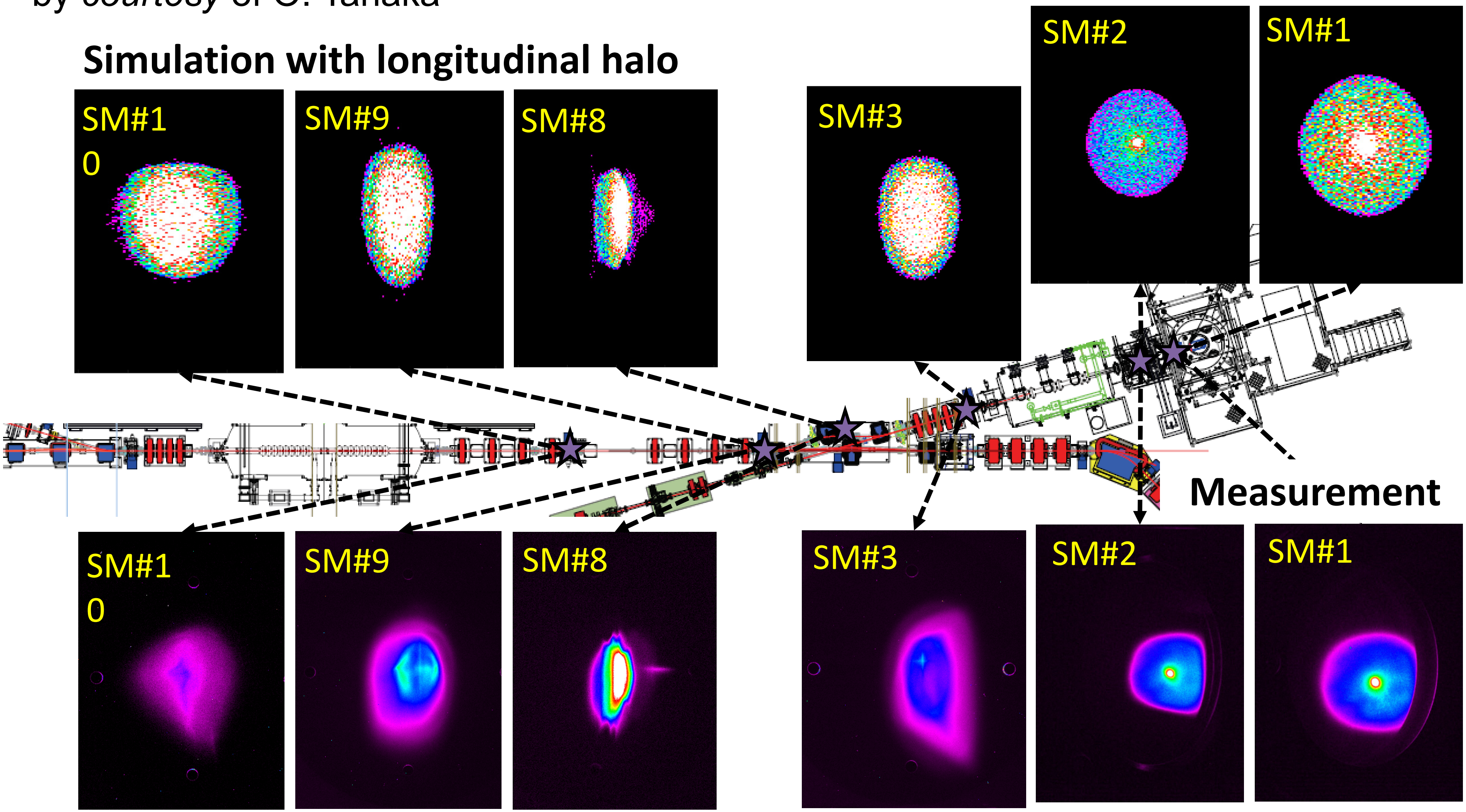
After optics tuning at MP2



Beam profiles after optics tuning

by *courtesy* of O. Tanaka

Simulation with longitudinal halo

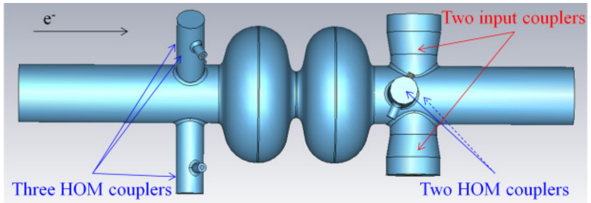


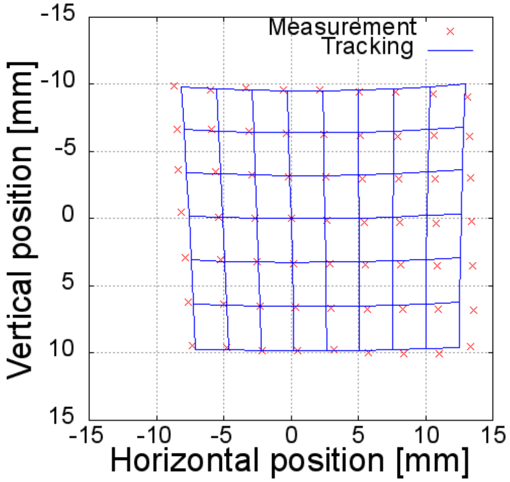
Measured beam sizes in injector

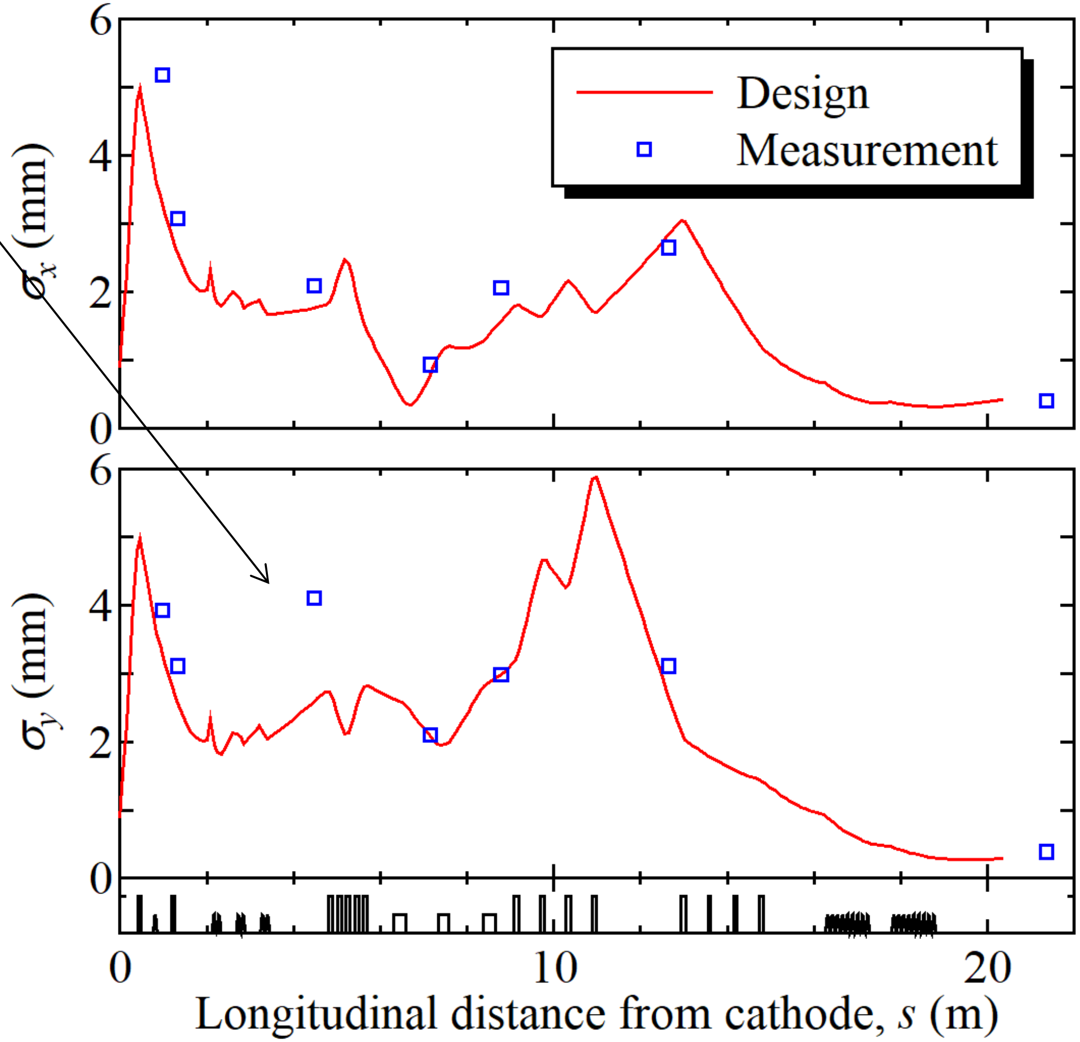
- The measured beam sizes well agreed with the design beam sizes except for the exit of injector.

- At the exit of injector, the measured vertical beam size is larger than the design.
- The beam size at the exit of injector is sensitive to the injection position and angle.

⇒ next study topic

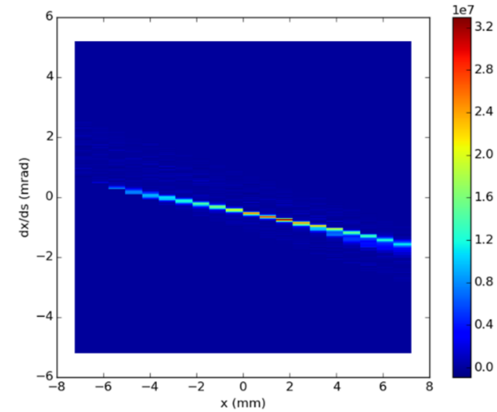


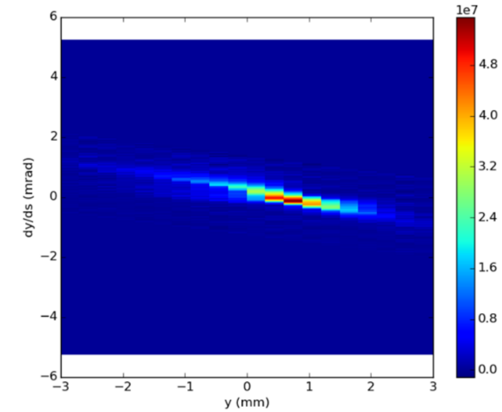




Emittance measurement by slit-scanner

- Transverse phase space distribution and emittance were measured by slit-scanner in the injector diagnostic line (without merger effect).

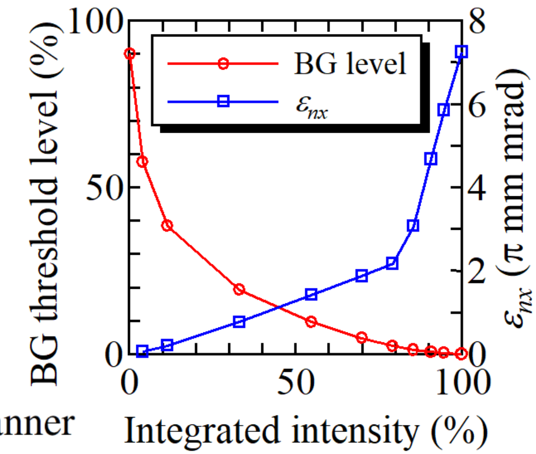




<u>Emittance calculation from phase space distribution</u>

To check the emittance analysis method, we calculate emittance by using two different methods.

- Analysis 1: Numerical integration with different background level
- Analysis 2: Fitting each slice



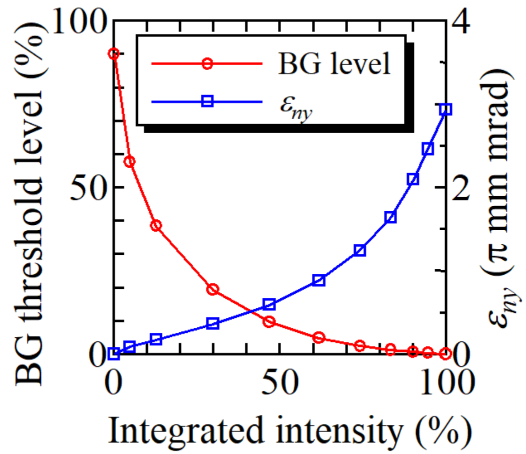


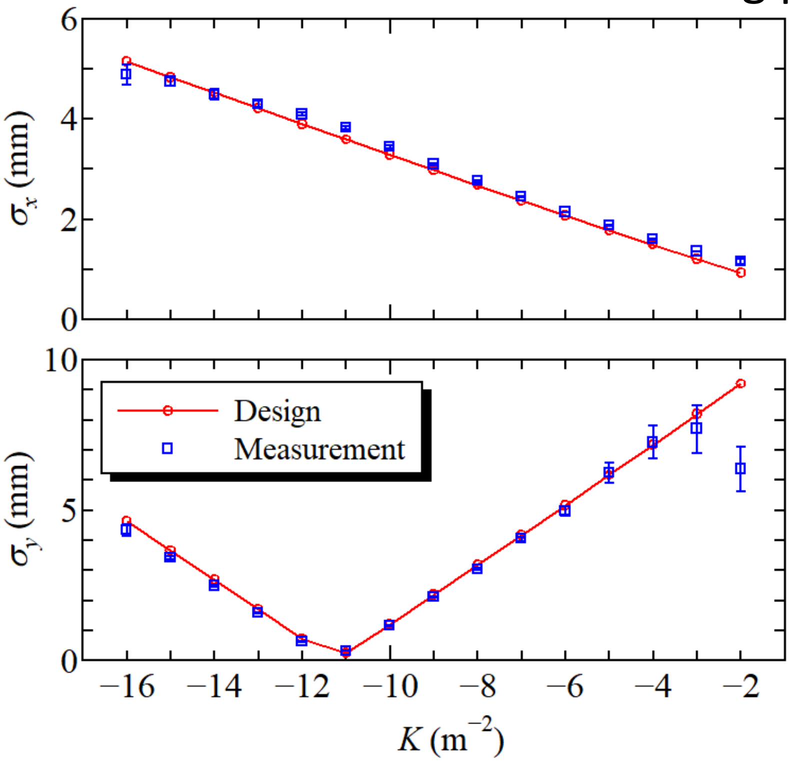
Table 1: Normalized RMS emittance at slit scanner

	Design	Analysis 1	Analysis 2
ε_{nx} (πmm · mrad)	1.42	1.87	1.937 ±0.286
ε_{ny} (πmm · mrad)	1.48	0.88	0.826 ±0.018

The difference from the design emittance still remains. However, we achieved < 3 π mm mrad.

Emittance for Main Linac and recirculation loop

- From Q-scan result at Matching point 2 (MP2), we calculate transverse emittance.

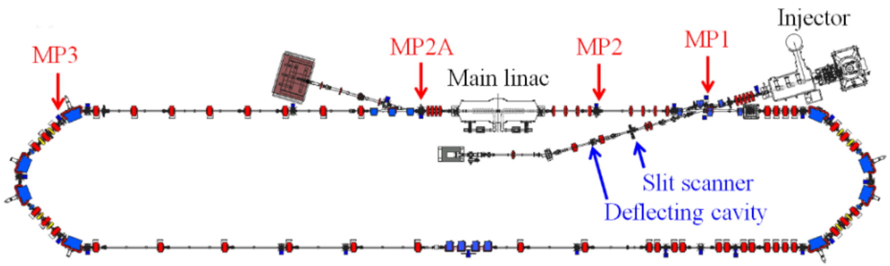


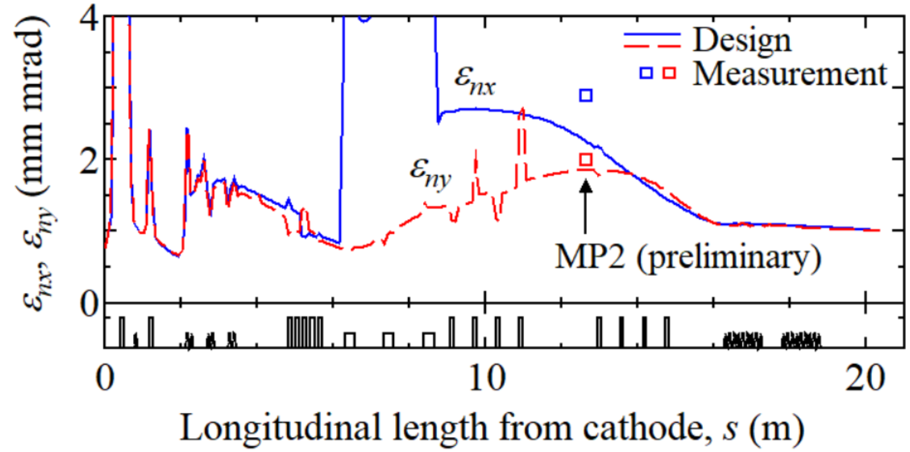
Horizontal emittance at MP2
(Preliminary result)

- Design: 2.26 π mm mrad
- Measured: 2.89 π mm mrad

Vertical emittance at MP2
(Preliminary result)

- Design: 1.86 π mm mrad
- Measured: 1.99 π mm mrad





The vertical emittance is good.
The difference of horizontal emittance still remains, but not so large.

Bunch length and energy spread

- We measured RMS bunch length and energy spread in the injector diagnostic line.

(1) Bunch length

By using deflecting cavity in the injector diagnostic line

- Design: 4.1 ps RMS
- Measurement: 4.5 ps RMS

Measured bunch length was slight longer, but not so bad.

(2) RMS Energy spread

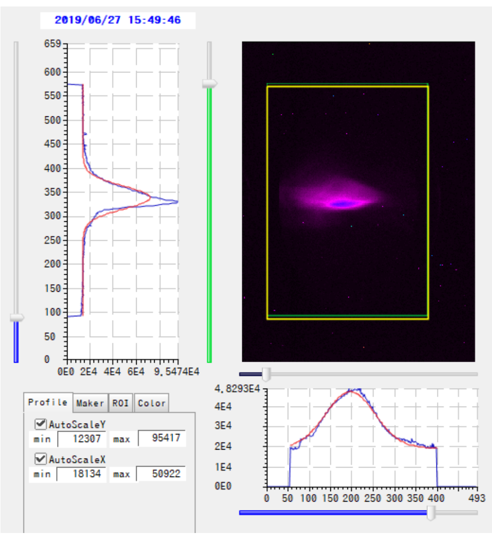
It was measured at a dispersive point in the injector diagnostic line.

- Design: 0.062 %
- Measurement: < 0.21 %

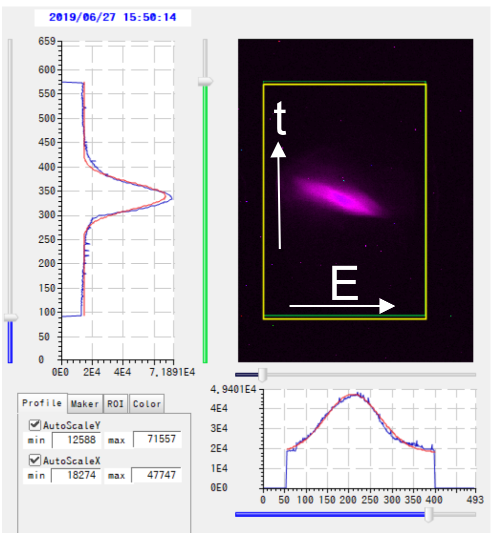
Measured energy spread is three times larger than the design value.
We require to find the cause of the difference. (Measurement method? Miss match of longitudinal dynamics?)

(3) Longitudinal phase space distribution (Preliminary)

Deflector off



Deflector on



In October 2019, we plan cERL beam operation with 60 pC.
We will continue to study the transportation of 60 pC beam.

Summary and next 60 pC operation in October 2019

- Summary of June 2019 operation
  - Transverse motion: Due to the improvement of accelerator model and the fine beam tuning, the beam condition of 60 pC was improved comparing with previous operation (until April 2019 operation).
  - Longitudinal motion: Single particle dynamics and bunch length are almost consistent to the design. However, we require to improve measurement and tuning of energy spread.

- After the injector tuning, we carried out systematic study about bunch compression in the first arc section.
  - Please see, ERL2019 poster presentation, WEPNEC11, "Beam Optics of Bunch Compression at Compact ERL" by M. Shimada.

- Next 60 pC operation in October 2019
  - The remained topics for injector: vertical beam size at the exit of injector, emittance compensation at the exit of Main Linac, energy spread
  - Beam transportation from the injector to recirculation loop, bunch compression and the IR-FEL points.

Summary

- We achieved very stable DC photocathode gun operation with 500 kV.
- The minimum discharge stop voltage is very good guide to do High Voltage conditioning of DC gun.

- In June 2019, we operated cERL with 60 pC bunch charge toward IR-FEL test.
- We improved beam transport condition for 60 pC bunch charge for both transverse and longitudinal motion.
- However, the difference from the design condition still remains. To correct them is next study topic.

- Next operation plan of cERL
  - October 2019, beam operation for 60 pC beam tuning (continued) and bunch compression study
  - (Nov. 2019 to Feb. 2020, Installation of an undulator for IR-FEL test)
  - March 2020, beam operation (Goal: to generate and observe the first IR-FEL light)

- To attend CBETA beam commissioning in March 2019 was exciting and good experience for me. I thanks to Steve Peggs, Georg Hoffstaetter, Karl Smolenski and CBETA team.

- cERL team welcomes persons to join the commissioning.

cERL team

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Thank you for your attention!