THC04
Session THC: Electron Bunch Generation and Manipulation

Beam Simulations of High Brightness Photocathode DC Gun and Injector for High Repetition FEL Light Source

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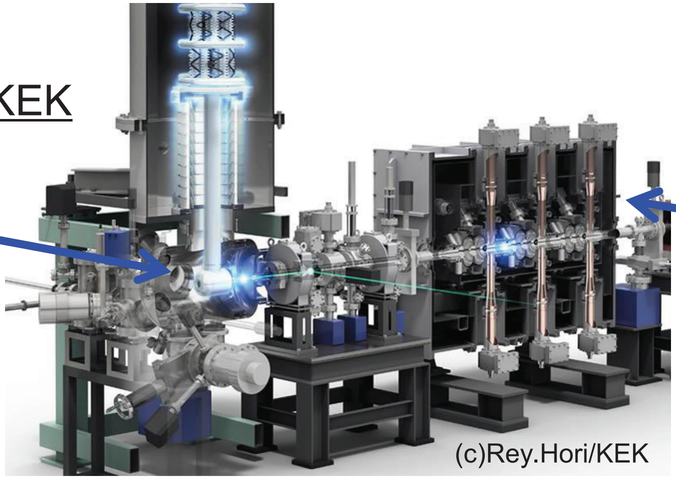
1. Introduction

Introduction

- FEL light source based on linac: LCLS, SACLA are being operating.
- As a next generation, high repetition rate operation to increase average FEL power has been proposed, e.g. LCLS-II project.
- The injector is important to generate high average current beam.
- High repetition rate injector
  - ERL injector: photocathode DC gun + superconducting cavity
  - 1.3 GHz operation of ERL injector has been demonstrated in Cornell University and KEK.
  - ERL injector can be employed for FEL injector.
  - Bunch charge: 77 pC (average 100 mA) for ERL ⇒ 300 pC for FEL

Injector for cERL in KEK

Photocathode DC gun
Cathode: GaAs
Target voltage: 500 kV



Injector cryomodule
1.3 GHz superconducting
Three 2-cell cavities
Target Eacc: 15 MV/m

- How about is the performance of the injector for FEL operation with high bunch charge?

Motivation and goal

- Target normalized emittance for high repetition FEL (from LCLC-II injector design)
  - 0.45 mm mrad for 100 pC
  - 0.7 mm mrad for 300 pC

C.F. Papadopoulos *et al.*, "RF Injector Beam Dynamics Optimization for LCLS-II", in Proc. of IPAC'14, Dresden, Germany, 2014, pp. 1974-1976.

- Demonstrated performance of cERL injector beam operation
  - Gun voltage: 390 kV (Target voltage: 500 kV)
  - Injector acceleration gradient, Eacc: 7 MV/m (Target Eacc: 15 MV/m)
  - Can we reach the target emittance based on the demonstrated performance?

- Motivation
  - To estimate the potential of ERL injector for high bunch charge operation with demonstrated hardware performance.
  - To estimate the effects of gun voltage and the injector acceleration gradient.

- Goal: to estimate the above things by particle tracking simulation
  - To obtain optimized injector parameters toward the target emittance
  - To investigate the effects of gun voltage and injector acceleration gradient on emittance

- We carried out injector optimizations using MOGA method.
  - Particle tracking code: GPT with 3D mesh space charge routine

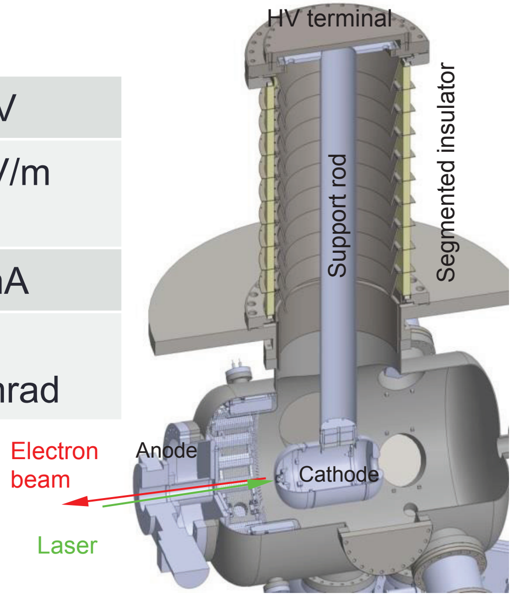
Ivan V. Bazarov *et al.*, Phys. Rev. ST Accel. Beams 8, 034202 (2005).

2. Demonstrated injector performance

Photocathode DC gun

Goals

High voltage	500 kV
Electric field on cathode	> 5MV/m
Beam current	100 mA
Normalized emittance	0.1-1 mm·mrad



The cERL photocathode gun was developed by JAEA.

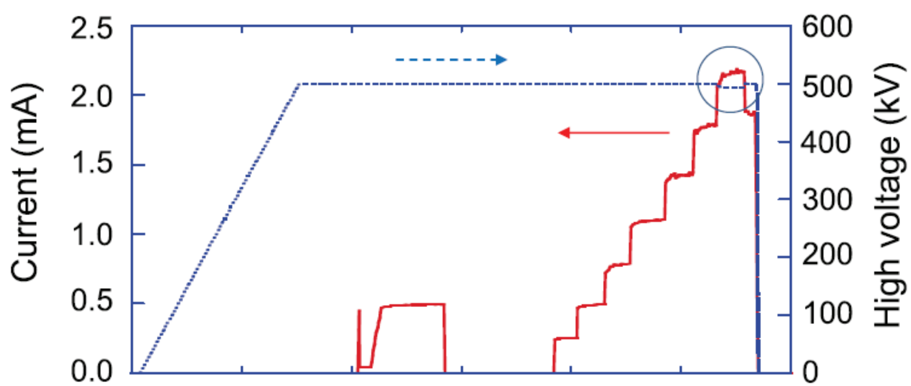
Performance at JAEA

- Successful production of 500-keV, 1.8-mA beams
- Electric field on cathode surface: 5.8 MV/m (@500 kV)

Performance at cERL

- Eight segments operation at 390 kV due to ceramic failure (found after transportation from JAEA to cERL).
- Normalized emittance: 0.07 mm·mrad @10fC (at cERL, V=390 kV)
- Long term operation (~ 260 hours) at V=390 kV at cERL

Successful production of 500-keV, 1.8 mA beam

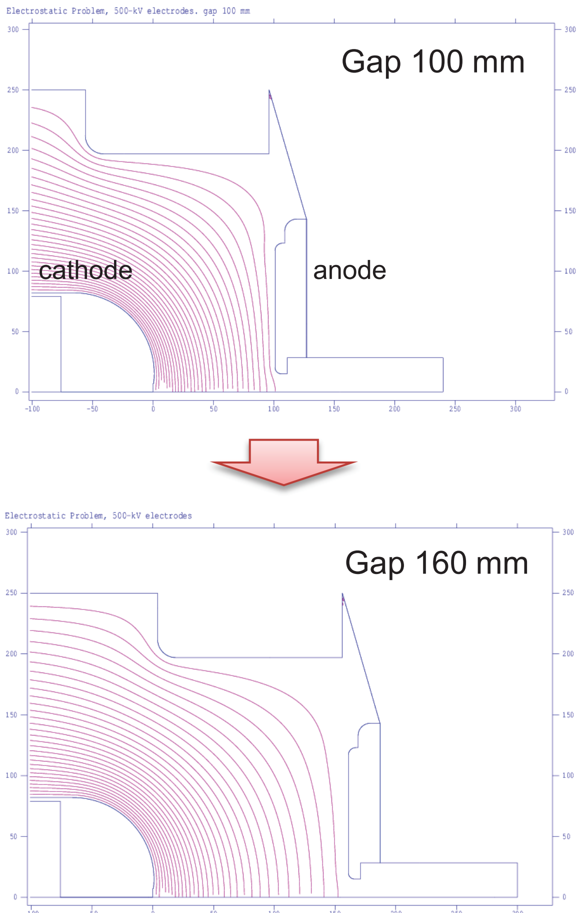


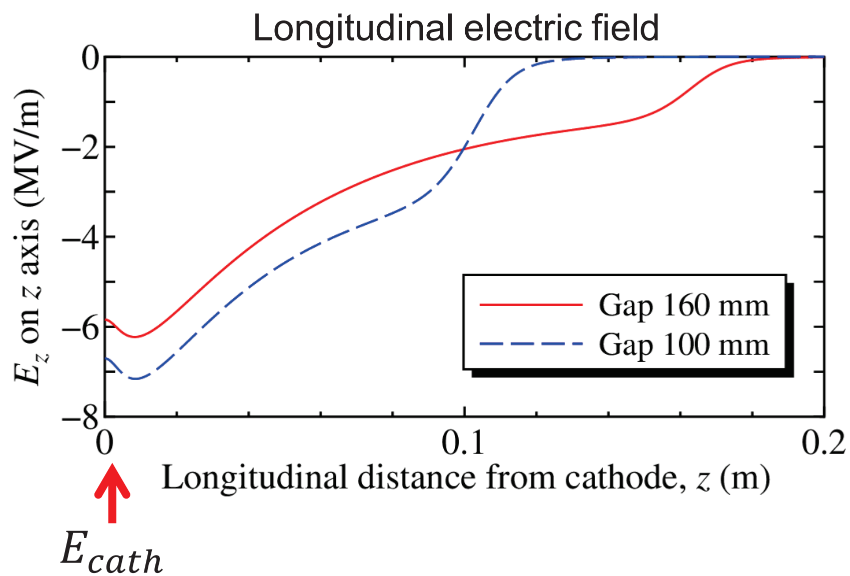
N. Nishimori et al., Appl. Phys. Lett. 102, 234103 (2013).

How about is the effect of the gun voltage for high bunch charge operation?

Gap of gun electrode

- To avoid discharge problem, we modified the gap between cathode and anode.
  - Gap: 100 mm ⇒ 160 mm
  - Electric field on cathode: 6.7 MV/m ⇒ 5.8 MV/m





The lowest normalized emittance from a photocathode DC gun depends on E_{cath}.

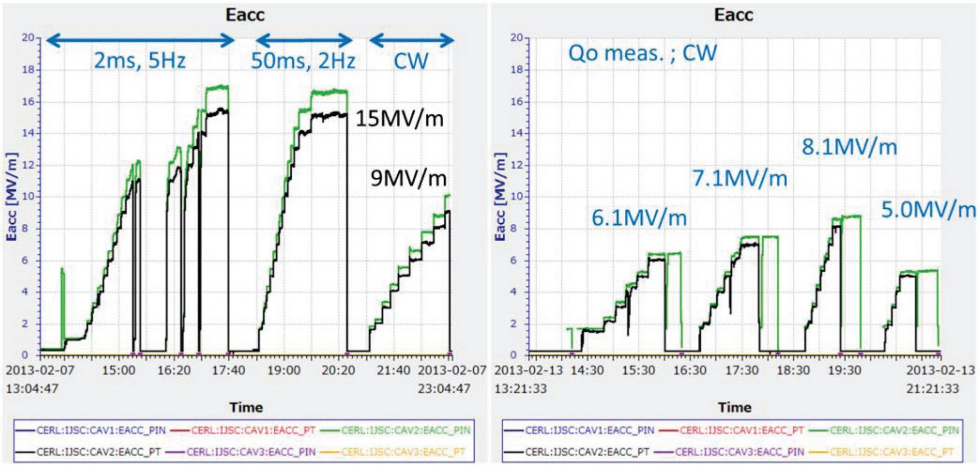
$$\epsilon_n \propto \sqrt{q \cdot \frac{k_B T}{E_{cath}}},$$

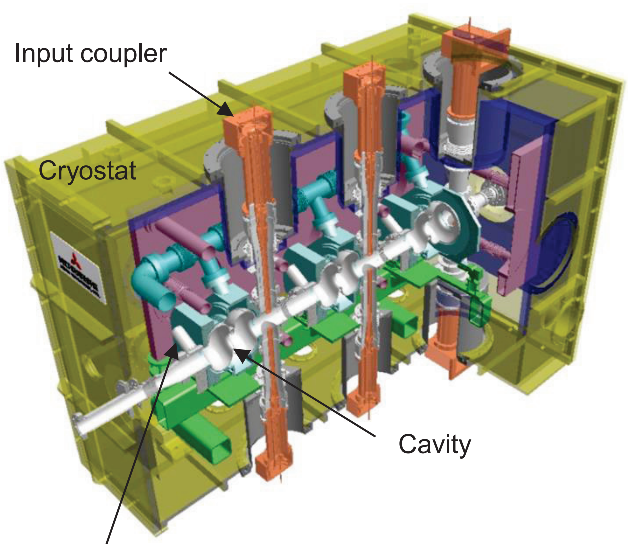
Ivan V. Bazarov *et al.* PRL **102**, 104801 (2009).
Colwyn Gulliford *et al.*, Phys. Rev. ST Accel. Beams16, 073401 (2013).

How about is the effect of the gap for high bunch charge operation?

Injector superconducting cavity

Processing of Cavity -2 : (2013, Feb. 7-8, 13)





E. Kako, et. al., proc. of ERL2013
S. Sakanaka,, proc. of ERL2013

Target E_{acc}: 15 MV/m, CW operation

HV processing of cavity

- E_{acc} = 15 MV/m was demonstrated for pulse operation with duty 10%
- E_{acc} = 8 MV/m was demonstrated for CW operation

cERL beam operation

- Stable CW operation (~260 hours) at E_{acc}=7.1 MV/m.
- Beam energy is 5.6 MeV at the exit of injector.

To accelerate the beam up to 10 MeV, 15 MV/m is required.

The cERL injector was optimized for 15 MV/m operation.

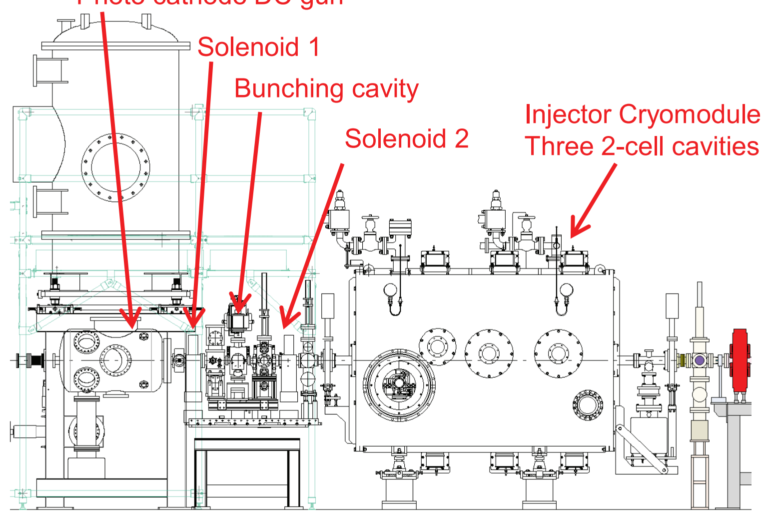
How about is the effect of E_{acc} for high bunch charge operation?

3. Injector simulations with high bunch charge

Two injector simulations

1. Effect of gun voltage for original cERL injector layout

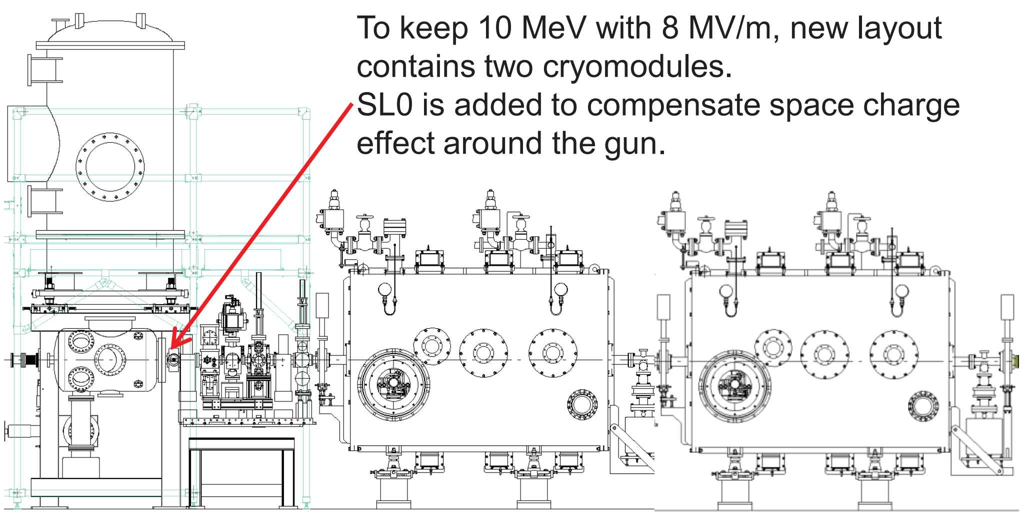
- Gun voltage: 300 – 600 kV
- E_{acc} of cavity: ~15 MV/m
- Injector energy: ~10 MeV
- Bunch charge: 100 pC and 300 pC
- Minimize emittance and gun voltage
- Element positions are fixed.
- Beam parameters were calculated at 6 m from cathode.
- Free parameters: gun voltage, laser diameter, laser pulse length, two solenoid strengths, buncher voltage and phase, E_{acc} and phases of SC1, 2, 3



2. Effect of injector acceleration gradient for new injector layout with two cryomodules

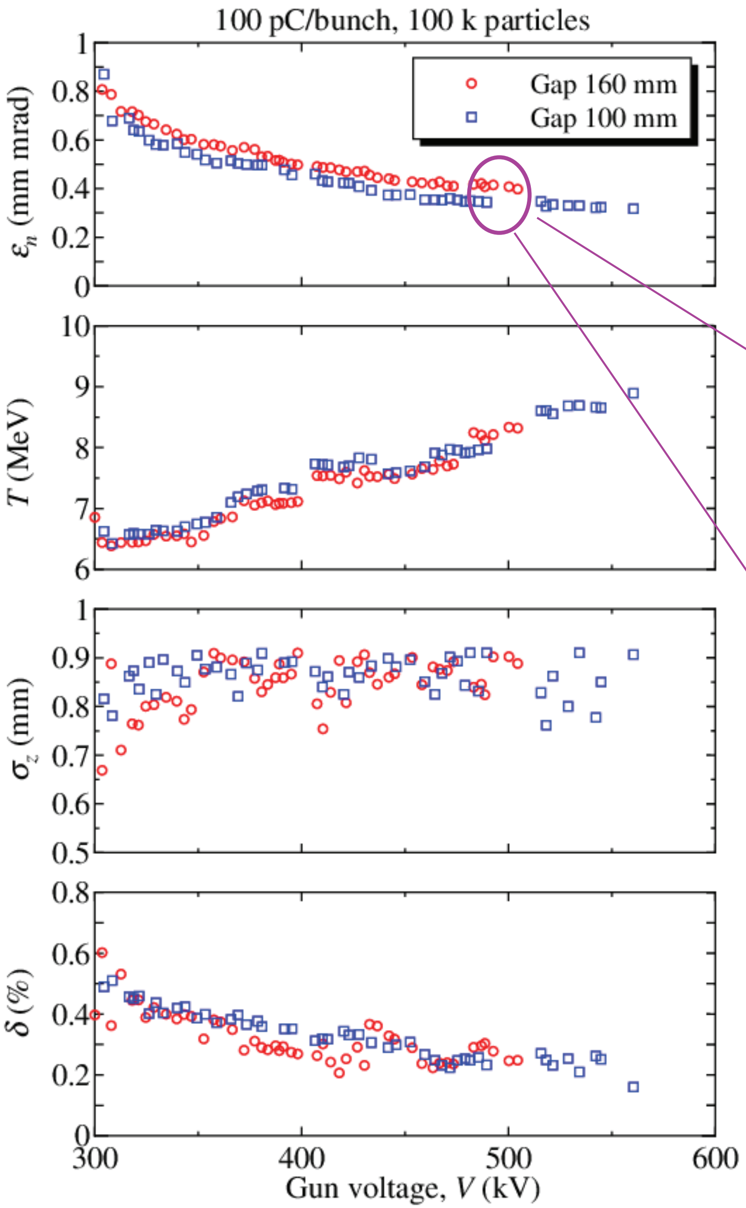
- Gun voltage: 500 kV
- E_{acc} of cavity: ~8 MV/m
- Injector energy: ~10 MeV
- Bunch charge: 325 pC
- Minimize emittance and bunch length
- Element positions are optimized.
- Beam parameters were calculated at 8 m from cathode.
- Free parameters: laser diameter, laser pulse length, three solenoid strengths, buncher voltage and phase, E_{acc} and phases of SC1, 2, 3, element positions

To keep 10 MeV with 8 MV/m, new layout contains two cryomodules.
SL0 is added to compensate space charge effect around the gun.

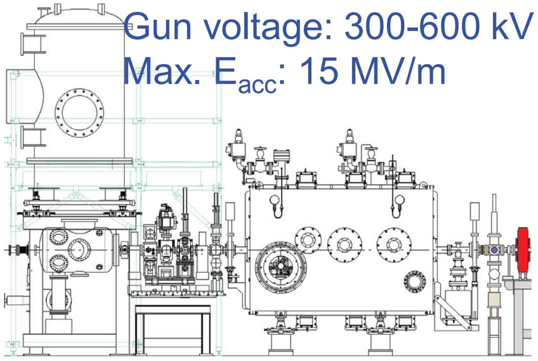


4. Optimization results

1. Effect of gun voltage for original layout



Bunch charge: 100 pC

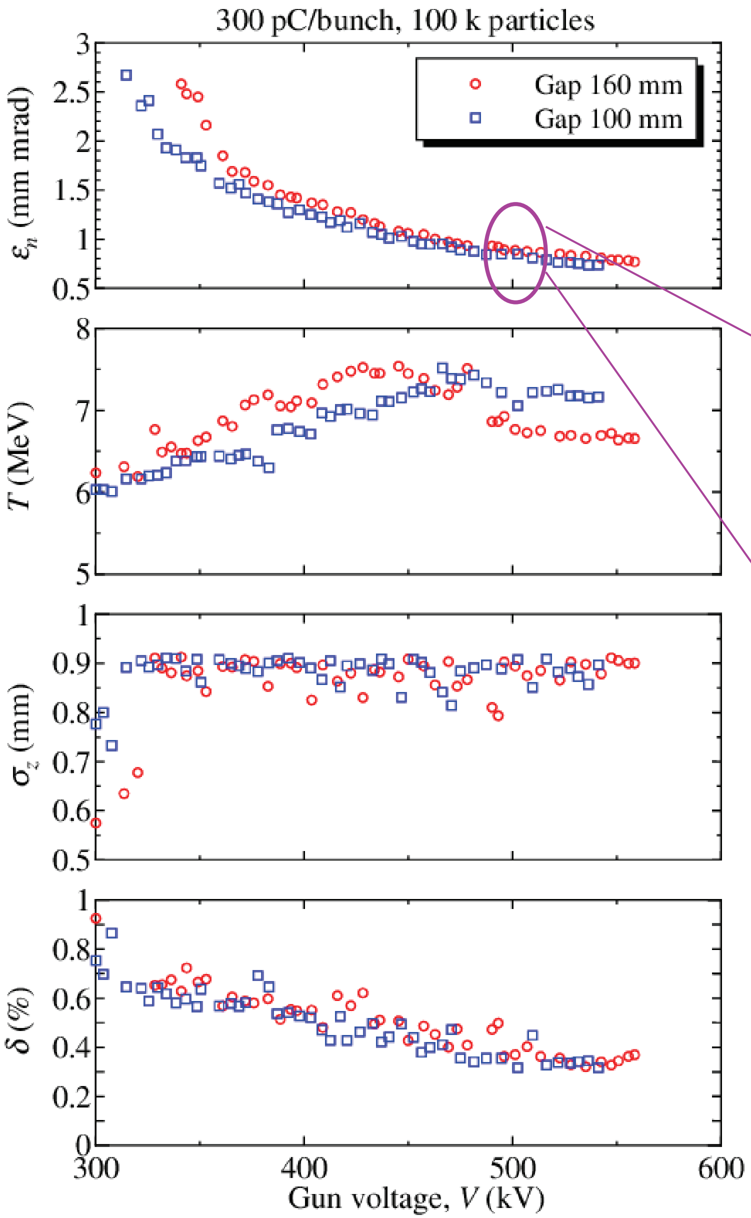


Gun voltage: 300-600 kV
Max. E_{acc}: 15 MV/m

For 500 kV gun voltage, project normalized rms emittance reached to 0.4 mm mrad.

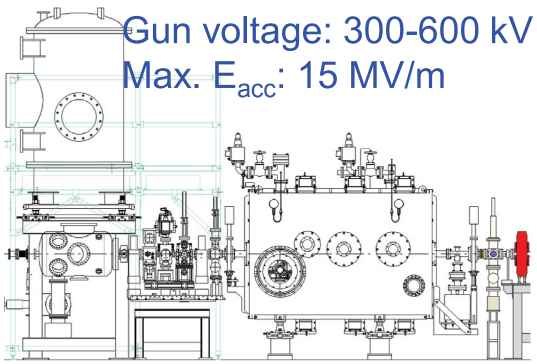
The gap of 100 mm gives lower emittance comparing with the gap of 160 mm. However, the effect of the gap on the emittance is less than 0.1 mm mrad.

The results shows that the cERL injector with E_{acc} of 15 MV/m can achieve the target emittance of 0.45 mm mrad for FEL operation.



Bunch charge: 300 pC

Gun voltage: 300-600 kV
Max. E_{acc}: 15 MV/m

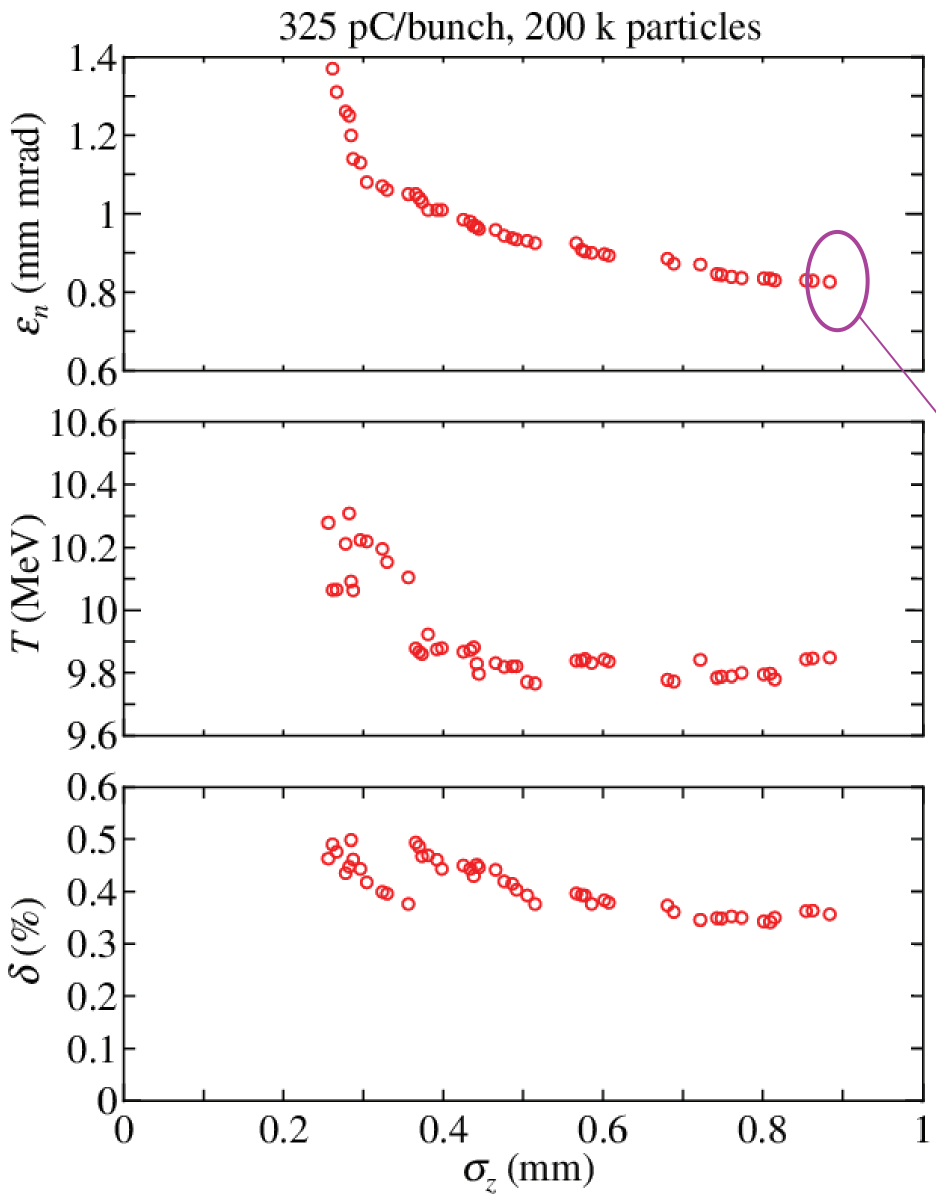


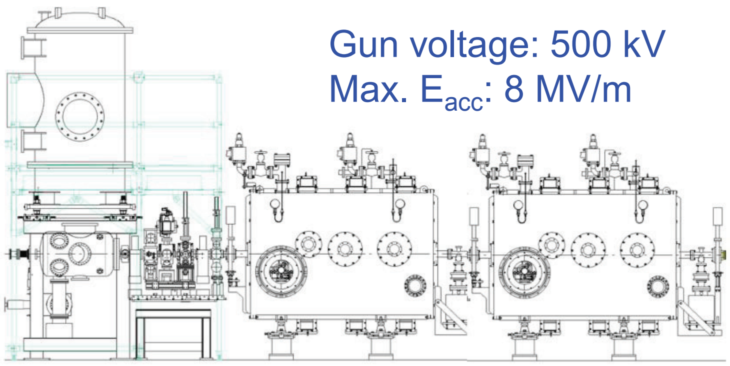
For 500 kV gun voltage, project normalized rms emittance reached to 0.8 mm mrad.

The gap of 100 mm gives lower emittance comparing with the gap of 160 mm. Compared with the results for 100 pC, the difference of emittance caused by the gap is smaller.

The minimum emittance of 0.8 mm mrad is close to the target emittance of 0.7 mm mrad for FEL operation.
The results show that higher gun voltage is better to achieve the target emittance.

2. Effect of cavity acceleration field for new layout



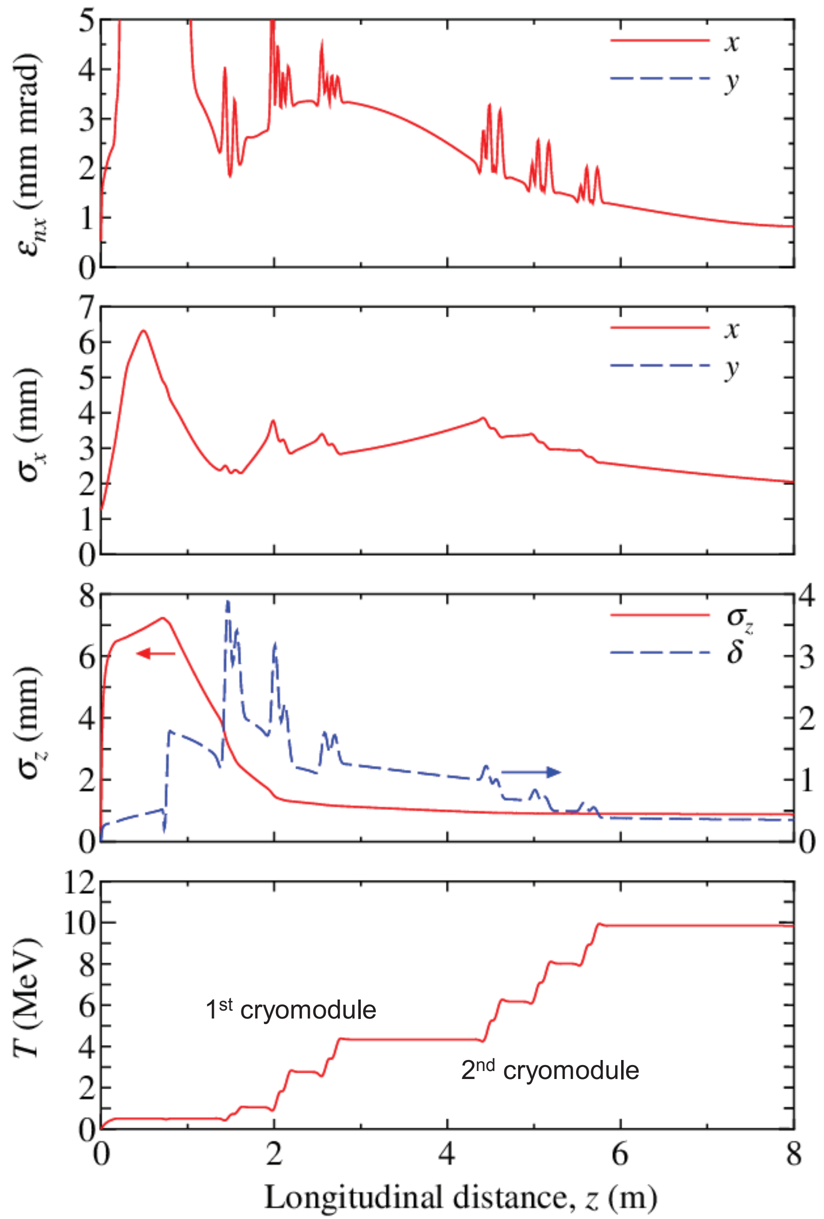


Gun voltage: 500 kV
Max. E_{acc}: 8 MV/m

For the bunch length of 0.9 mm, the projected normalized emittance is 0.8 mm mrad.

The results show that the new layout with two cryomodules and the maximum E_{acc} of 8 MV/m can also achieve 0.8 mm mrad.
This value is close to the target emittance of 0.7 mm mrad.

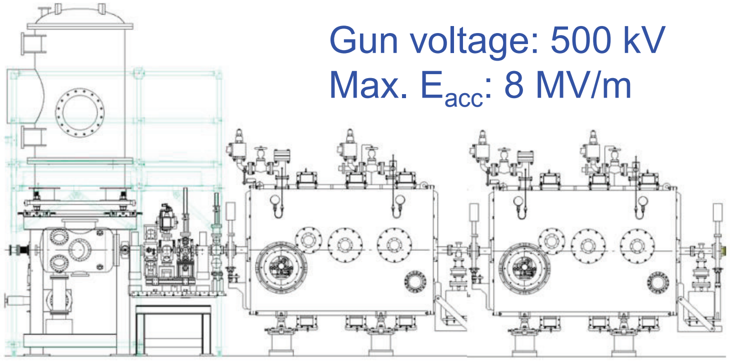
Optimized parameters and time evolution



325 pC

0.8 mm mrad

Gun voltage: 500 kV
Max. E_{acc}: 8 MV/m



Parameter	Value
Laser diameter	5.06 mm
Laser pulse length (FWHM)	73.4 ps
Gun voltage	500 kV
Magnetic field of SL0	0.0356 T
Magnetic field of SL1	0.0299 T
Magnetic field of SL2	0.0109 T
Buncher voltage	115 kV
E_{acc} of SC1	2.98 MV/m
E_{acc} of SC2	7.98 MV/m
E_{acc} of SC3	7.97 MV/m
E_{acc} of SC4-6	8.00 MV/m
Buncher phase	-89.0 degree
Phase of SC1	-25.8 degree
Phase of SC2	-14.4 degree
Phase of SC3	-29.7 degree
Phases of SC4-6	0 degree

The both optimizations show that an ERL injector has potential to achieve the target for FEL operation

5. Summary

Summary

- For high repetition rate operation of FEL light source based on linac, injector simulations were carried out based on ERL injector, which consists of a photocathode DC gun and superconducting RF cavities.
- The performance of the injector components were already demonstrated on the cERL beam operation in KEK.

- Based on the demonstrated hardware performance, we optimized the injector parameters to achieve the requirement for high repetition rate FEL, and investigated the effects of gun voltage and acceleration gradient of injector cavity using the original injector layout and new layout with two injector cryomodules.

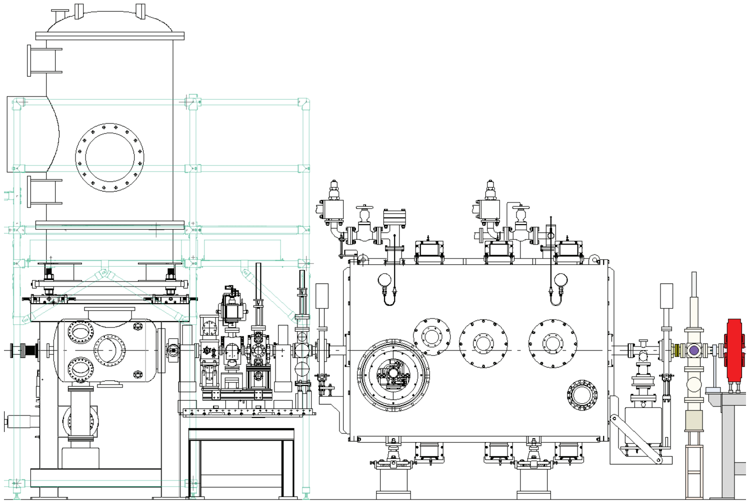
- The optimization results show that the gun voltage of 500 kV is helpful to achieve low emittance, and the both original and new layouts have potential to achieve target emittance for FEL operation.

- Next step is to design realistic layout of elements based on the optimization results.

Backup slides

Two injector simulations

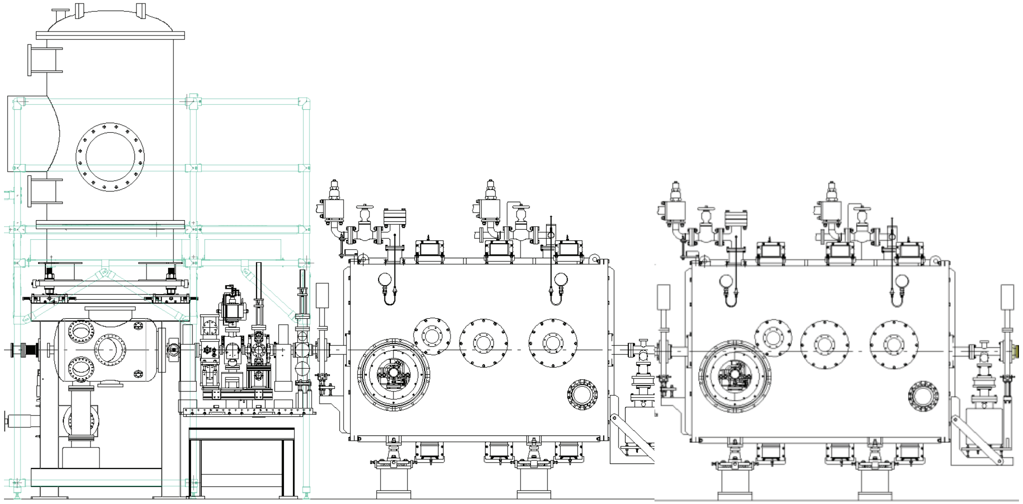
1. Effect of gun voltage for original cERL injector layout



2. Effect of injector acceleration gradient for new injector layout with two cryomodule

Table 1: Center positions of injector elements from cathode surface

Element	Original cERL (m)	New layout (m)
SL0	-	0.294
SL1	0.445	0.494
BC	0.809	0.752
SL2	1.218	0.909
SC1	2.221	1.519
SC2	2.781	2.079
SC3	3.341	2.639
SC4	-	4.519
SC5	-	5.079
SC6	-	5.639

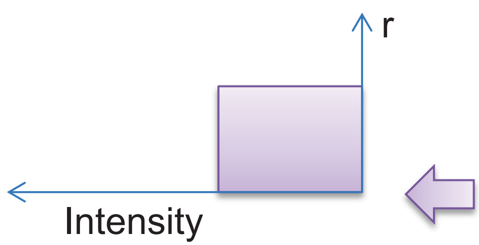


Initial laser condition

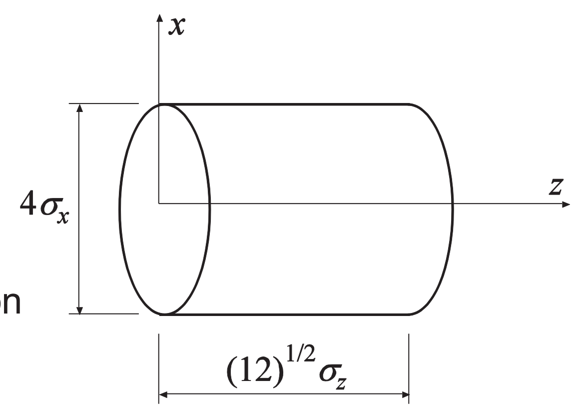
- Photo electron is emitted from a photo cathode when laser is applied on it.
- Emitted electron beam from the cathode strongly depends on initial laser condition.

Initial laser condition	**Emitted electron beam**
Laser spot size, *d*	Transverse beam size
Laser pulse width	Bunch length
Laser power	Bunch charge
Laser wave length	Initial emittance ($k_B T$)

Laser distribution ⇒ beer-can shape



Transverse profile: uniform distribution



Initial emittance

$$\epsilon_n = \frac{d}{4}\sqrt{\frac{k_B T}{mc^2}}$$

$k_B T$ in this simulaiton: 90 meV

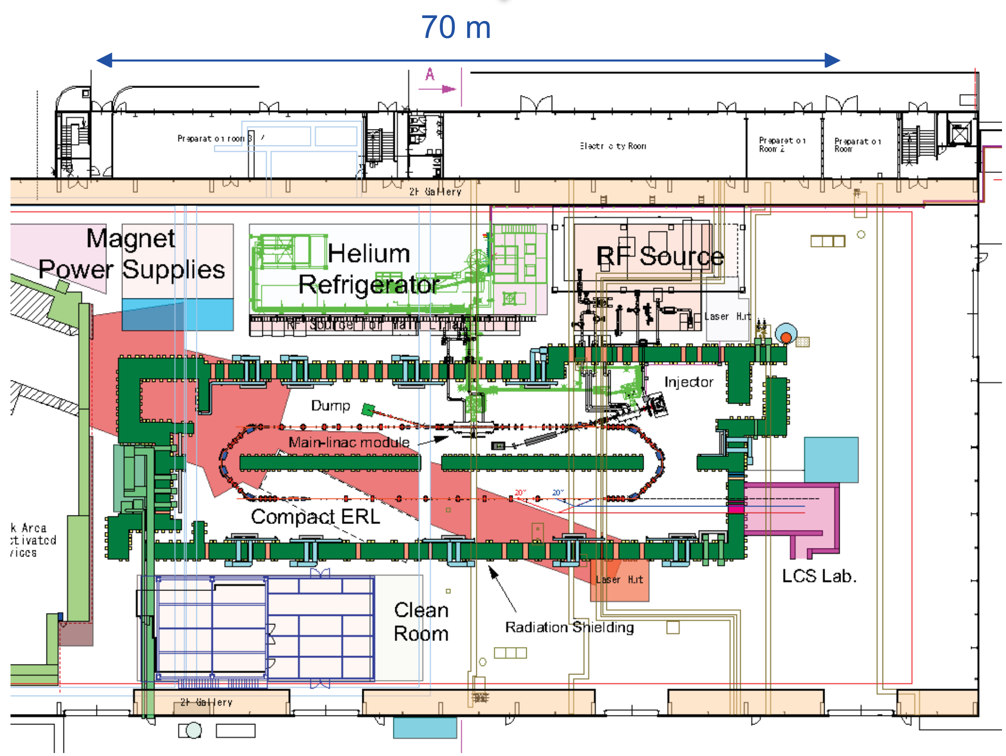
Longitudinal profile: uniform distribution

compact ERL in KEK

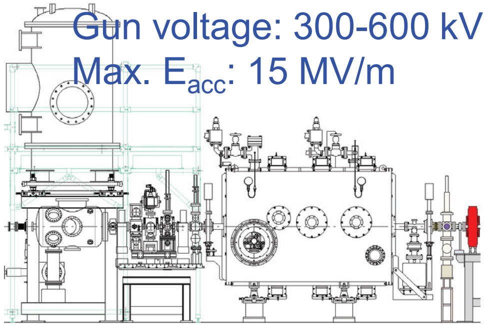
- compact ERL (cERL): a test accelerator to develop Energy Recovery Linac

Parameters of the Compact ERL

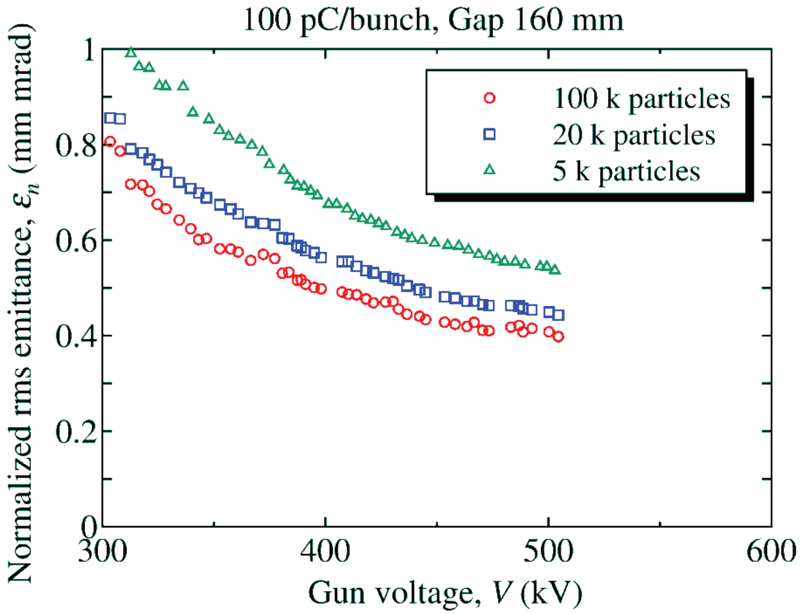
	Parameters
Beam energy (upgradability)	35 MeV 125 MeV (single loop) 245 MeV (double loops)
Injection energy	5 MeV
Average current	10 mA (100 mA in future)
Acc. gradient (main linac)	15 MV/m
Normalized emittance	0.1 mm·mrad (7.7 pC) 1 mm·mrad (77 pC)
Bunch length (rms)	1 - 3 ps (usual) ~ 100 fs (with B.C.)
RF frequency	1.3 GHz



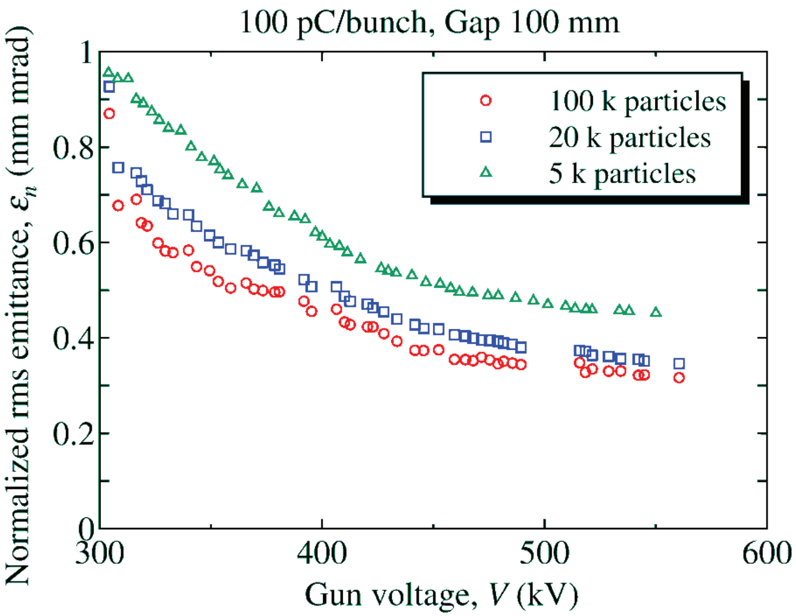
Effect of number of macro-particles



Effect of number of particles



Gap of gun: 160 mm



Gap of gun: 100 mm