PA06

KEK
Unravelling the mysteries of matter, life and the universe.

Injector optimization for the IR-FEL operation at the Compact ERL at KEK

Olga TANAKA

on behalf of cERL team

Accelerator laboratory

High Energy Accelerator Research Organization, KEK

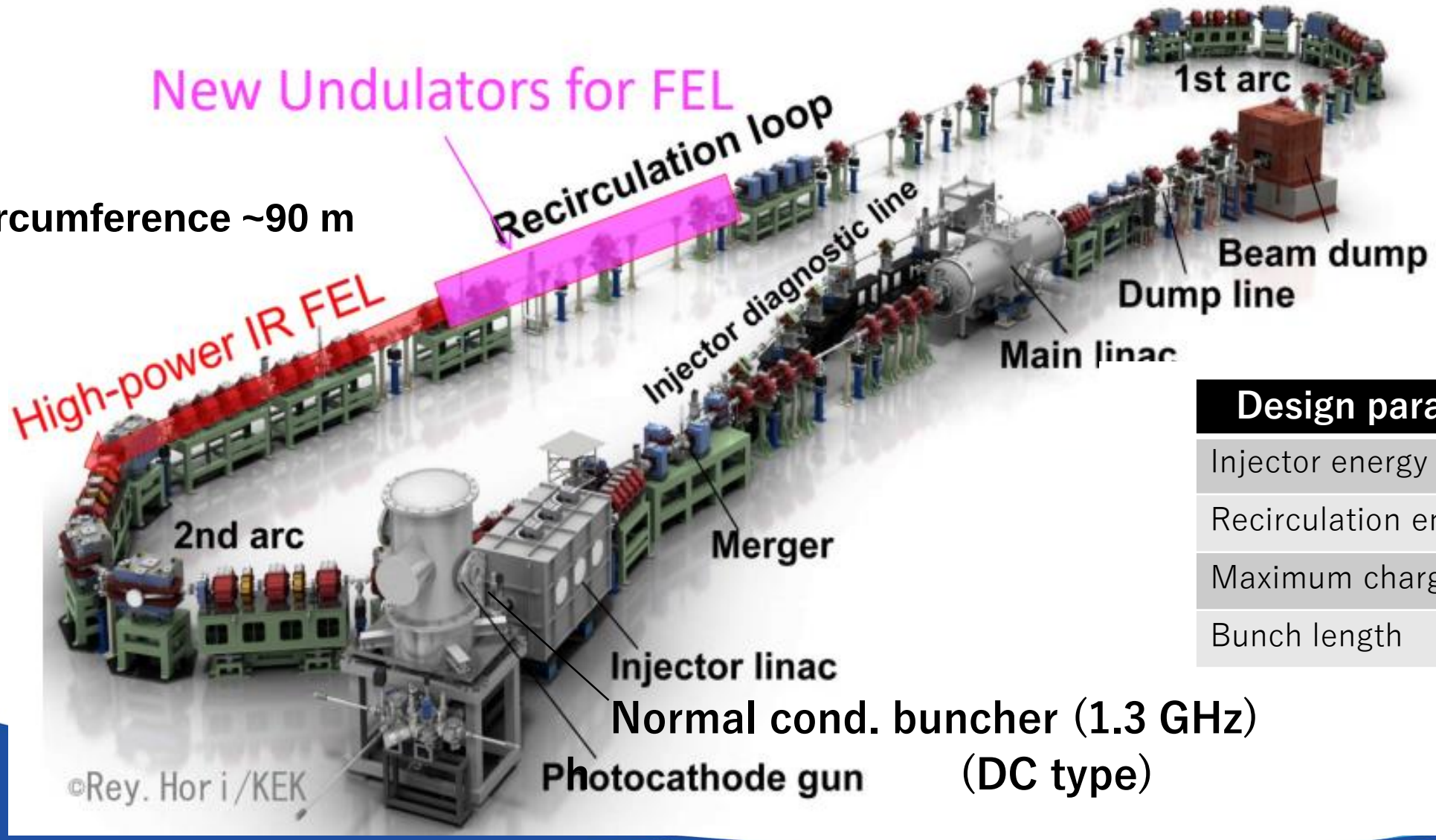
Abstract

The Compact Energy Recovery Linac at KEK is a test accelerator to develop ERL technologies and to operate with a high average beam current and a high beam quality. cERL consists of a photoinjector, a main linac for energy recovery, a recirculation loop and a beam dump. A recent upgrade of the cERL to the middle Infrared Free Electron Laser (IR-FEL) imposed new conditions to maintain beam parameters. Therefore, the injector should be optimized to meet the following requirements at the exit of the main linac. The rms bunch length should be 2 ps, the rms longitudinal emittance should be kept the least, and simultaneously the rms transverse emittance should be kept less than 3 pi mm mrad. In this work we describe the strategy and results of the injector optimization to achieve the better performance of the cERL-FEL.

olga@post.kek.jp

Introduction
Middle Infrared (MIR)-FEL using Compact ERL

Circumference ~90 m

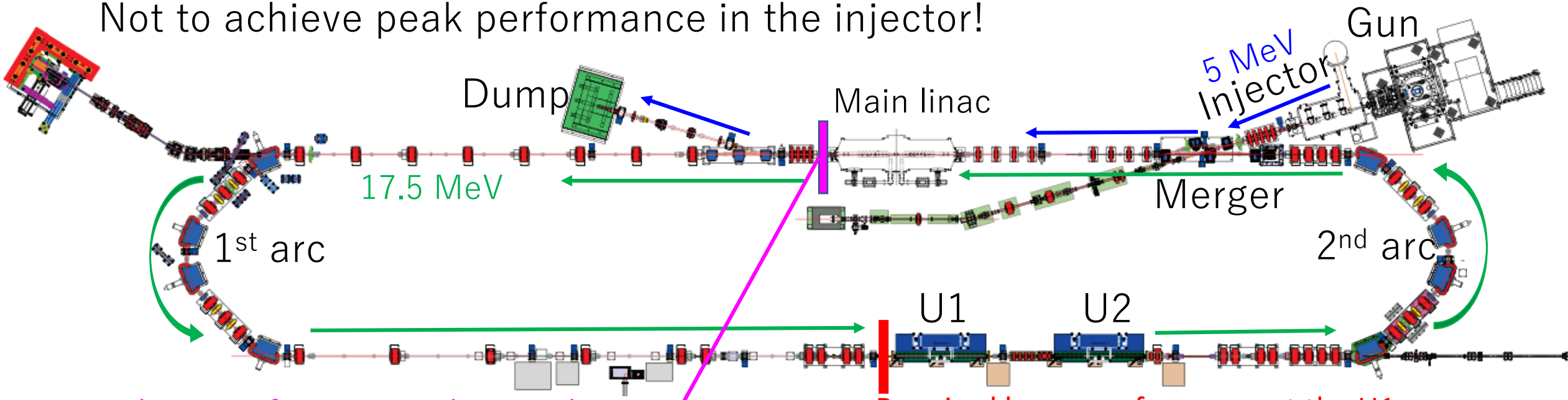


Design parameters of the cERL	
Injector energy	5 MeV
Recirculation energy	17 - 20 MeV
Maximum charge current	60 pC
Bunch length	1-3 ps

Injector optimization

Targets

- Main goal: Follow the operation conditions to generate and to transport appropriate beam to the undulator entrance for IR-FEL light production. Not to achieve peak performance in the injector!



- Target beam performance at the Main linac exit:
  - Bunch charge : 60 pC
  - Bunch length : 2 ps (rms) (The bunch is compressed in the first arc section.)
  - Energy spread : 0.1%
  - Norm. rms emittance : < 3 π mm mrad

- Required beam performance at the U1:
  - Bunch charge : 60 pC
  - Repetition rate : 1.3 GHz
  - Bunch length : 0.5 – 2 ps (FWHM)
  - Energy spread : 0.1%
  - Norm. rms emittance : 3 π mm mrad

Injector optimization

Challenges in Jun. 2020 vs Feb.–Mar. 2021

- The beam performance is assured by the stable and high accelerating voltage supply of the 500 kV DC gun.
- Due to trouble caused by misoperation in Nov. 2020, the voltage of the photocathode DC gun dropped 500 kV → 480 kV. **Can the necessary beam performance still be achieved?**
- The beam performance results based on the simultaneous minimization of the bunch length and the transverse emittance was not satisfactory for FEL light production, since the bunch compression in the arc was not enough. **How about to concentrate on the longitudinal emittance optimization?**
- An additional task was to investigate the influence of the initial laser temporal distribution. Previously a single Gaussian was used in the model, but the real structure is a seven stacked Gaussian pulses.

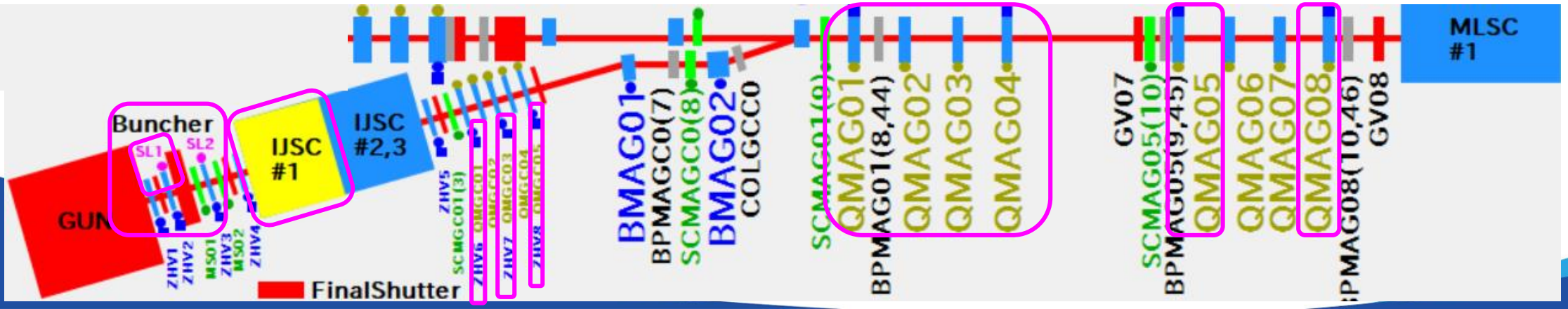
	Jun. 2020 operation	Feb.–Mar. 2021 operation
Electron gun voltage	500 kV	480 kV
Optimization objective	Simultaneous minimization of bunch length and transverse emittance	Simultaneous minimization of bunch length and longitudinal emittance

Injector optimization
Setup

- Injector optimization: General Particle Tracer (GPT) with Multi Objective Genetic Algorithm (MOGA)
- Objectives: Simultaneously minimize bunch length and longitudinal emittance at the exit of the Main linac.

Constrants
RMS bunch length < 1.8 ps
Transverse rms emittance < 3.0 π mm mrad
Betatron function β_x < 8.0 m; β_y < 20.0 m
Alpha function -2.0 < α_x < 0.0; -0.5 < α_y < 0.5

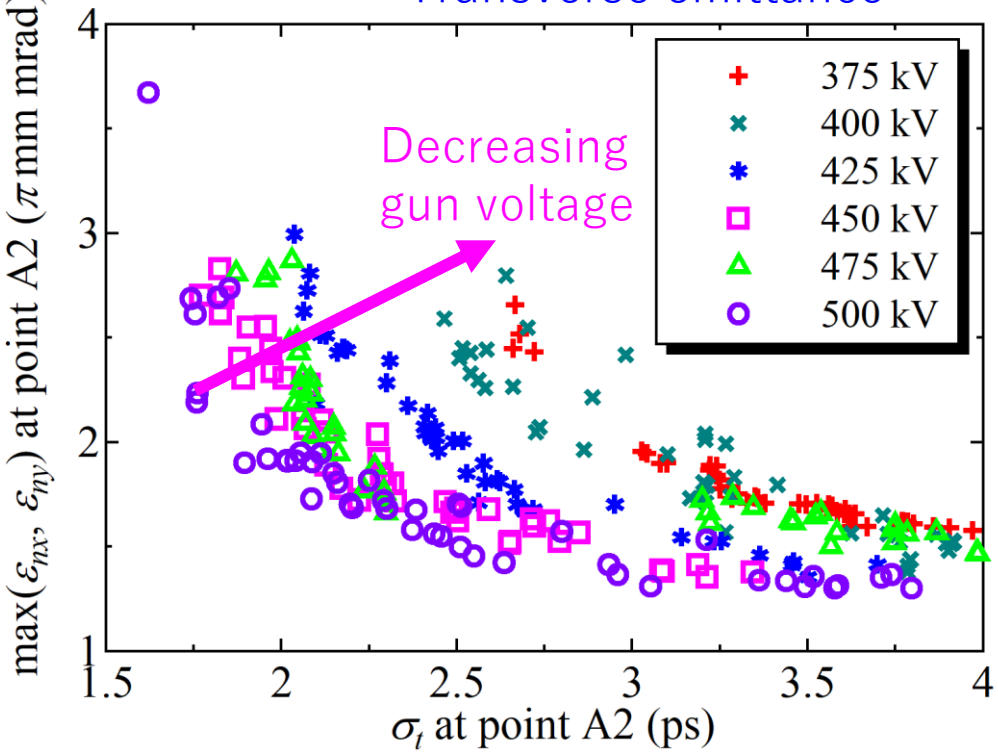
- Optimization parameters of MOGA (13 variables) are shown in magenta in the lattice below.



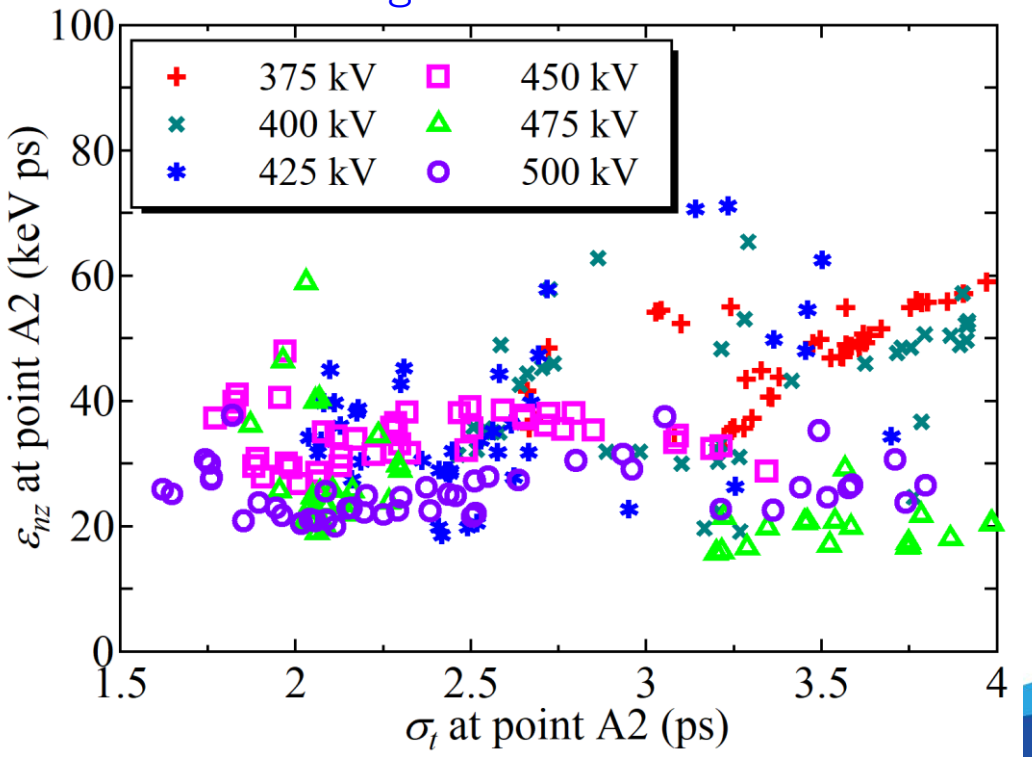
Injector optimization
Gun voltage and beam performance

- What kind of beam performance can be transported to the main cavity exit when this drops to 400 kV?
- The optimization demonstrated no big difference in the beam performance for gun voltages in the range 450 - 500 kV.
- However, the voltage less than 425 kV essentially degrades the bunch length (2ps should be kept).
- Taking into account DC gun conditioning results, the value of **480 kV** was decided for the following optimization.

Transverse emittance



Longitudinal emittance

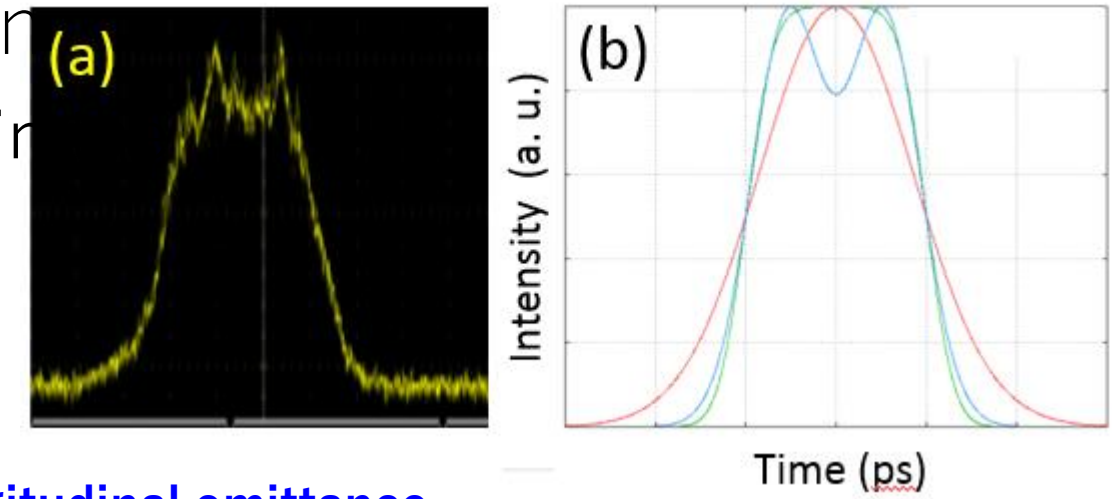


Injector optimization

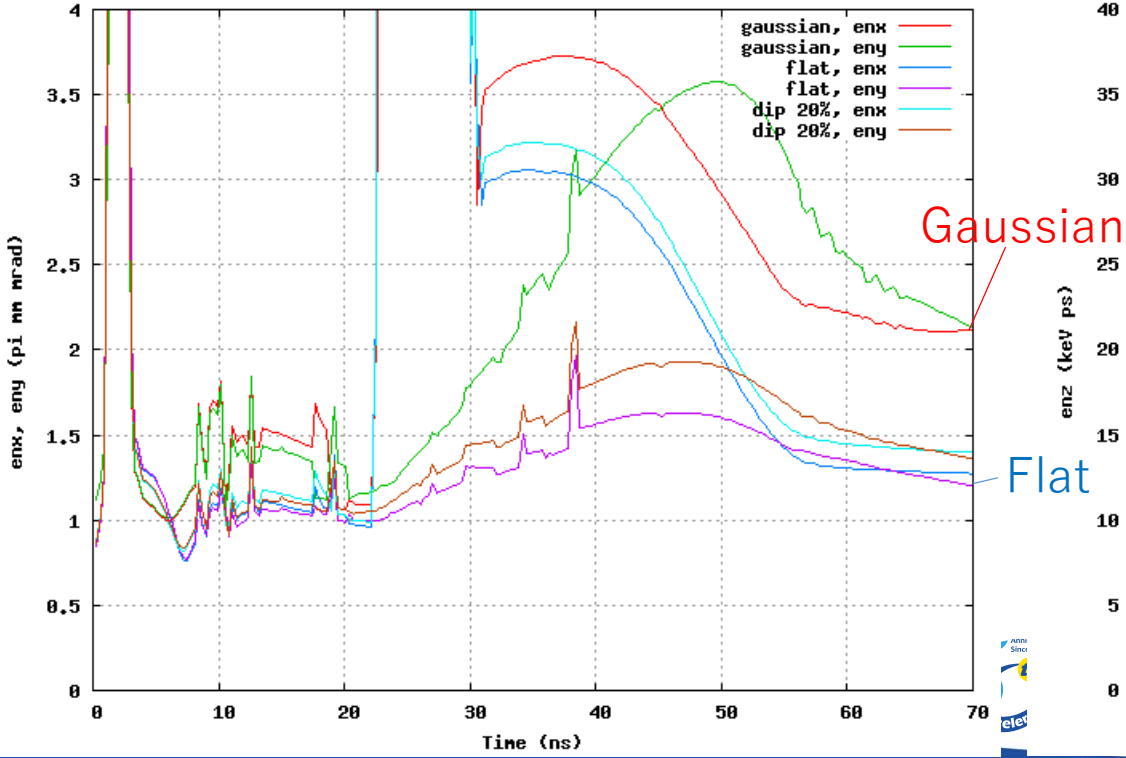
Effect of initial laser time distribution

- To reproduce a real laser time structure in simulation, 3 possibilities were studied:
  - 40 ps FWHM single Gaussian;
  - 40 ps FWHM flat;
  - 40 ps FWHM flat with 20% dip.

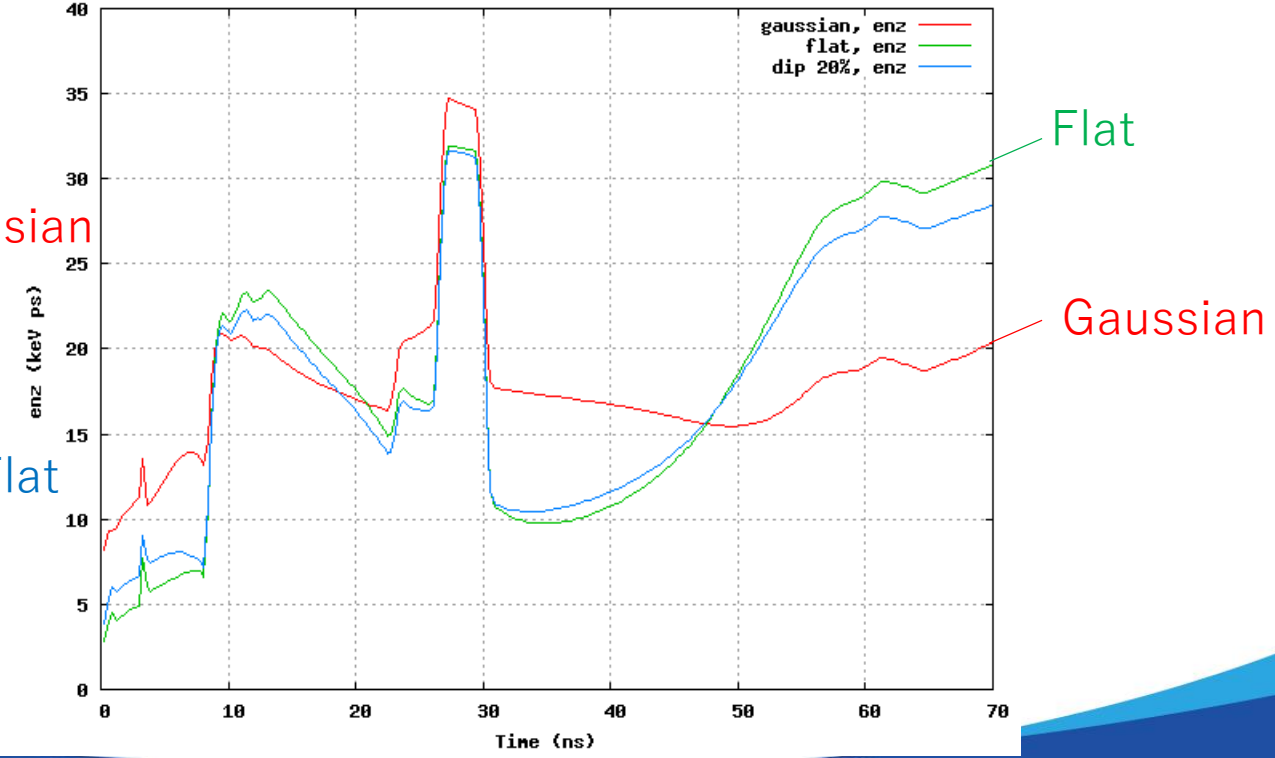
Real laser pulse



Transverse emittance



Longitudinal emittance

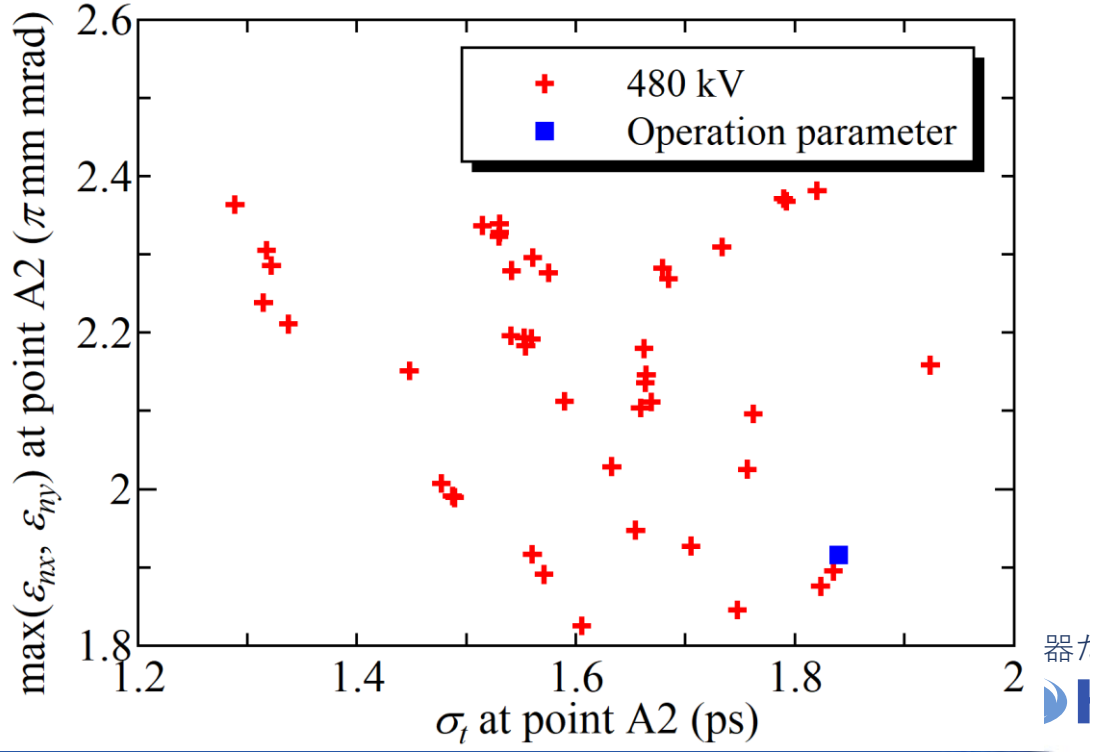


Injector optimization

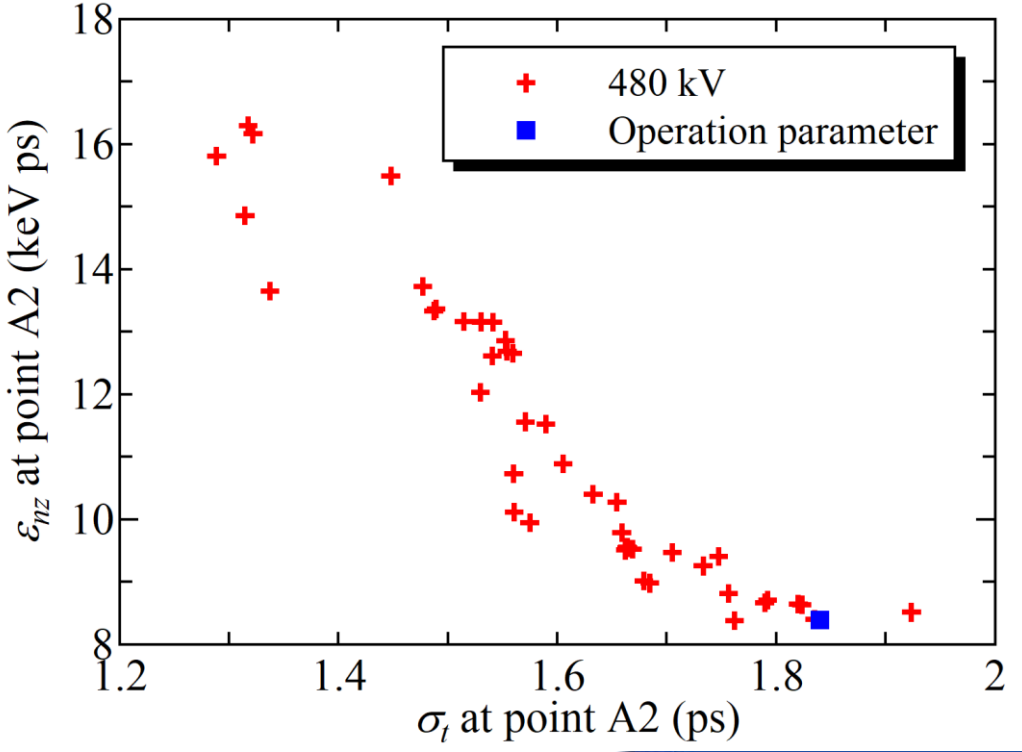
Result of simultaneous minimization of bunch length and longitudinal emittance at 480 kV

- The variety of 50 choices of injector settings are represented.
- One setting includes 3 values: the bunch length, the transverse emittance, and the longitudinal emittance.
- **Blue square:** bunch length: 1.8 ps, transverse emittance: 1.9 π mm mrad, longitudinal emittance: 8.4 keV ps.

Transverse emittance at the Main Linac exit



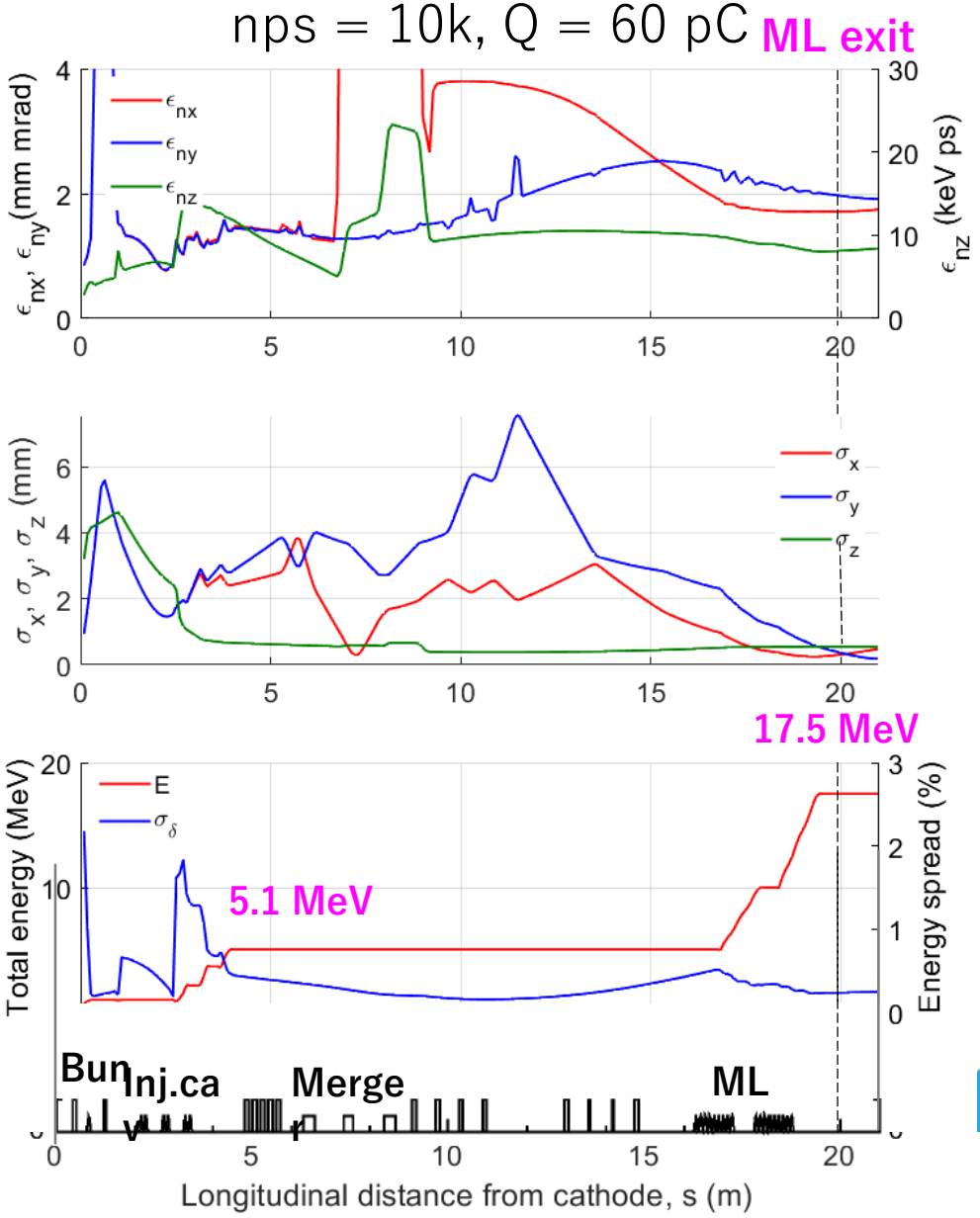
Longitudinal emittance at the Main Linac exit



Injector optimization
Injector optics design

- Operation parameters in Feb. – Mar. 2021:
  - Electron gun voltage: 480 kV.
  - Injector energy: 5.1 MeV.
  - Bunch charge: 60 pC.
  - Laser time structure: flat, FWHM 40 ps.
  - Laser XY distribution: radial Gaussian (rms = 1.191 mm) + 2 mm pinhole.
- Designed beam performance at the exit of the Main Linac:
  - Normalized rms transverse emittance ε_{nx}, ε_{ny} : 1.74, 1.92 π mm mrad.
  - Normalized rms longitudinal emittance ε_{nz} : 8.4 keV ps.
  - RMS transverse beam size σ_x, σ_y : 0.69, 0.35 mm.
  - RMS bunch length σ_z : 1.8 ps.
  - RMS energy spread : 0.25%.
  - β_x = 4.26 m; β_y = 0.61 m.
  - α_x = -1.82; α_y = 0.16.

Time evolution for FEL production,
nps = 10k, Q = 60 pC



Summary

- We achieved an appropriate beam performance at the exit of the main linac by injector optimization with respect to:
  - Electron gun voltage 480 kV;
  - Laser initial temporal distribution 40 ps FWHM flat-top;
  - Simultaneous minimization of bunch length and longitudinal emittance at the exit of the main linac cryomodule.
- In Feb. – Mar. 2021 we were able to achieve a FEL pulse energy of about 5.8 nJ per electron bunch.
- Comparison of the designed performance and measured results demonstrated a good agreement in the transverse motion. However, longitudinal motion needs additional investigations for bunch compression in the recirculation loop. To evaluate it is next study topic.
- Next operation plan of cERL:
  - CW operation with energy recovery.
  - Beam current increase up to 10 mA.