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

10:30-10:50, May 28, 2021

12th International Particle Accelerator Conference - IPAC’21 (virtual)

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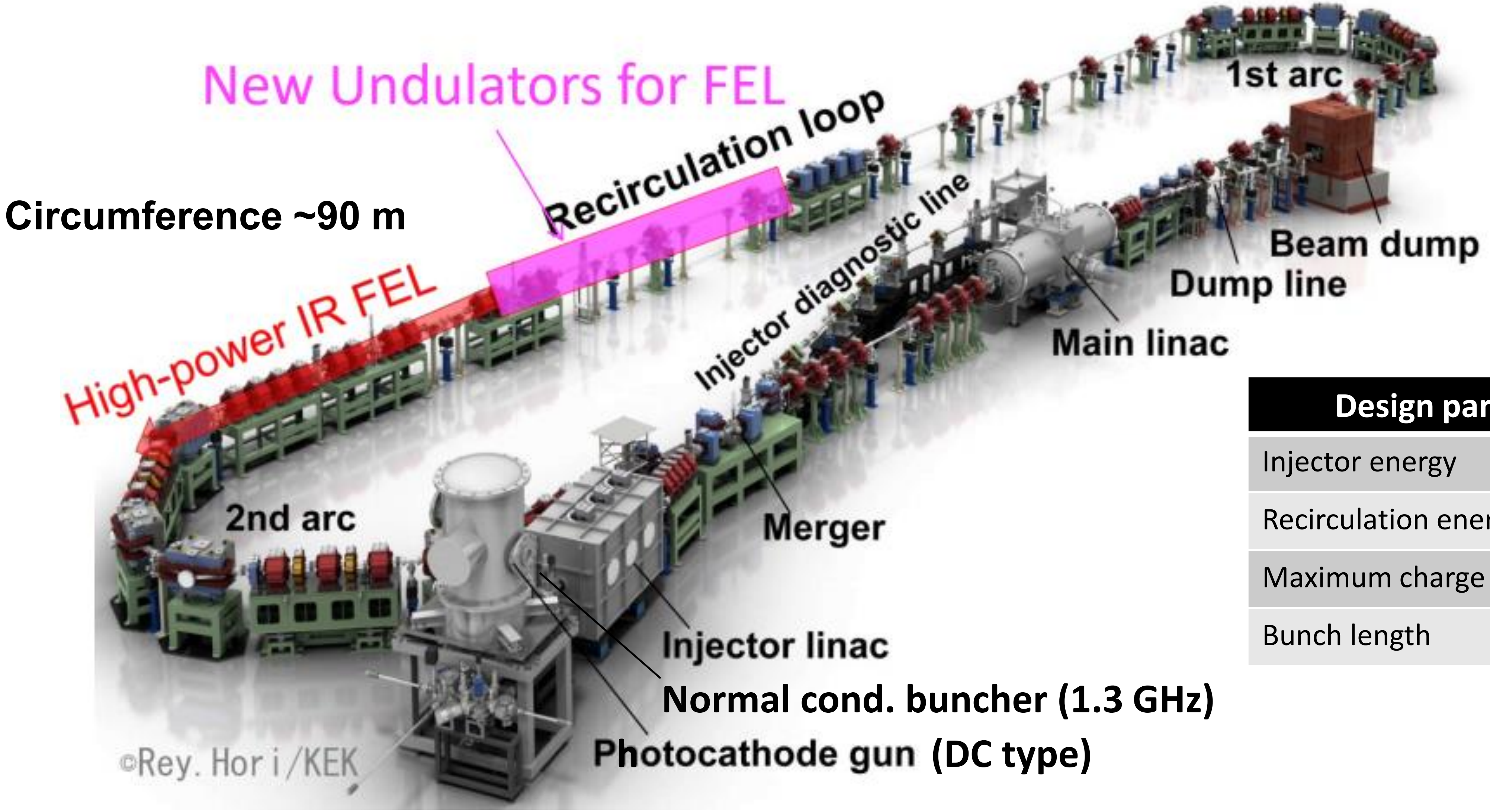
KEK, High Energy Accelerator Research Organization

On behalf of cERL team

Agenda

- Introduction
- Injector optimization
  - Targets
  - Challenges
  - Important remarks
  - Setup
  - Gun voltage vs beam performance
  - Effect of initial laser time distribution
  - Simultaneous minimization
  - Injector optics design
- Comparison of the designed performance and measured results
  - Buncher tuning
  - Optics matching
  - Beam profiles after optics tuning
  - Measured beam sizes
  - Emittance for recirculation loop
- Summary

Introduction
Middle Infrared (MIR)-FEL using Compact ERL

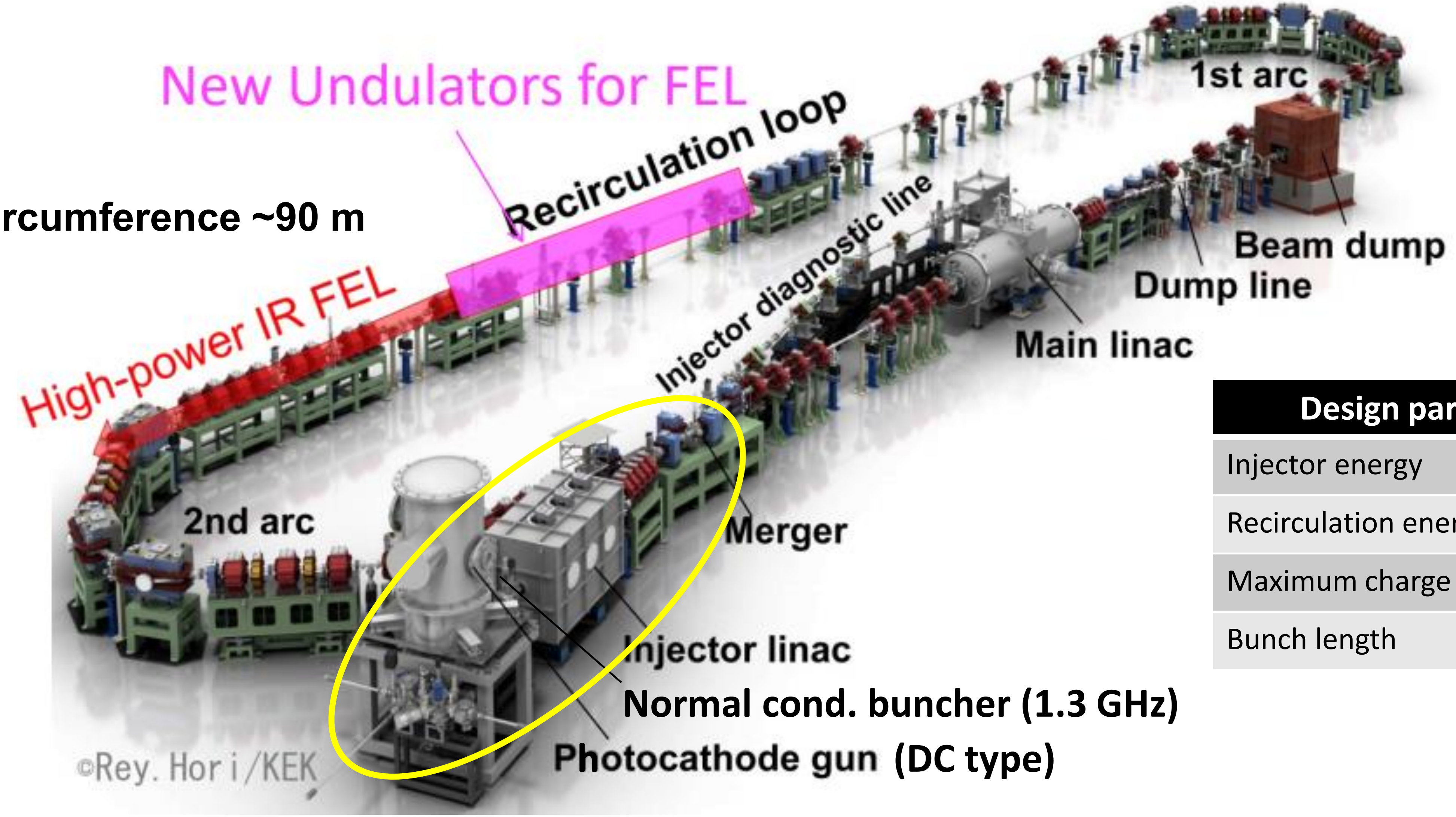


Design parameters of the cERL	
Injector energy	5 MeV
Recirculation energy	17 - 20 MeV
Maximum charge current	60 pC
Bunch length	1-3 ps

Introduction

Middle Infrared (MIR)-FEL using Compact ERL

Circumference ~90 m



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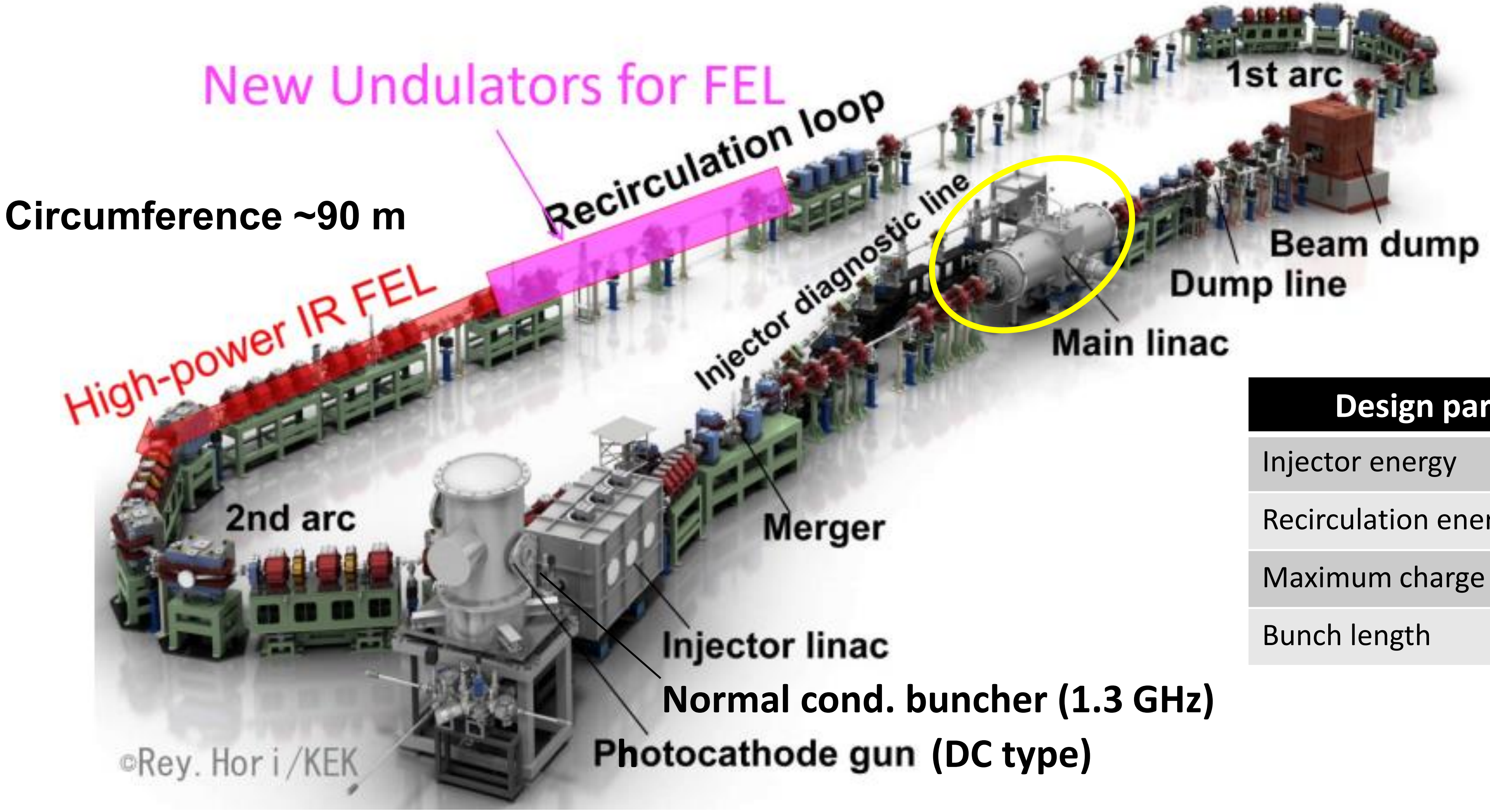

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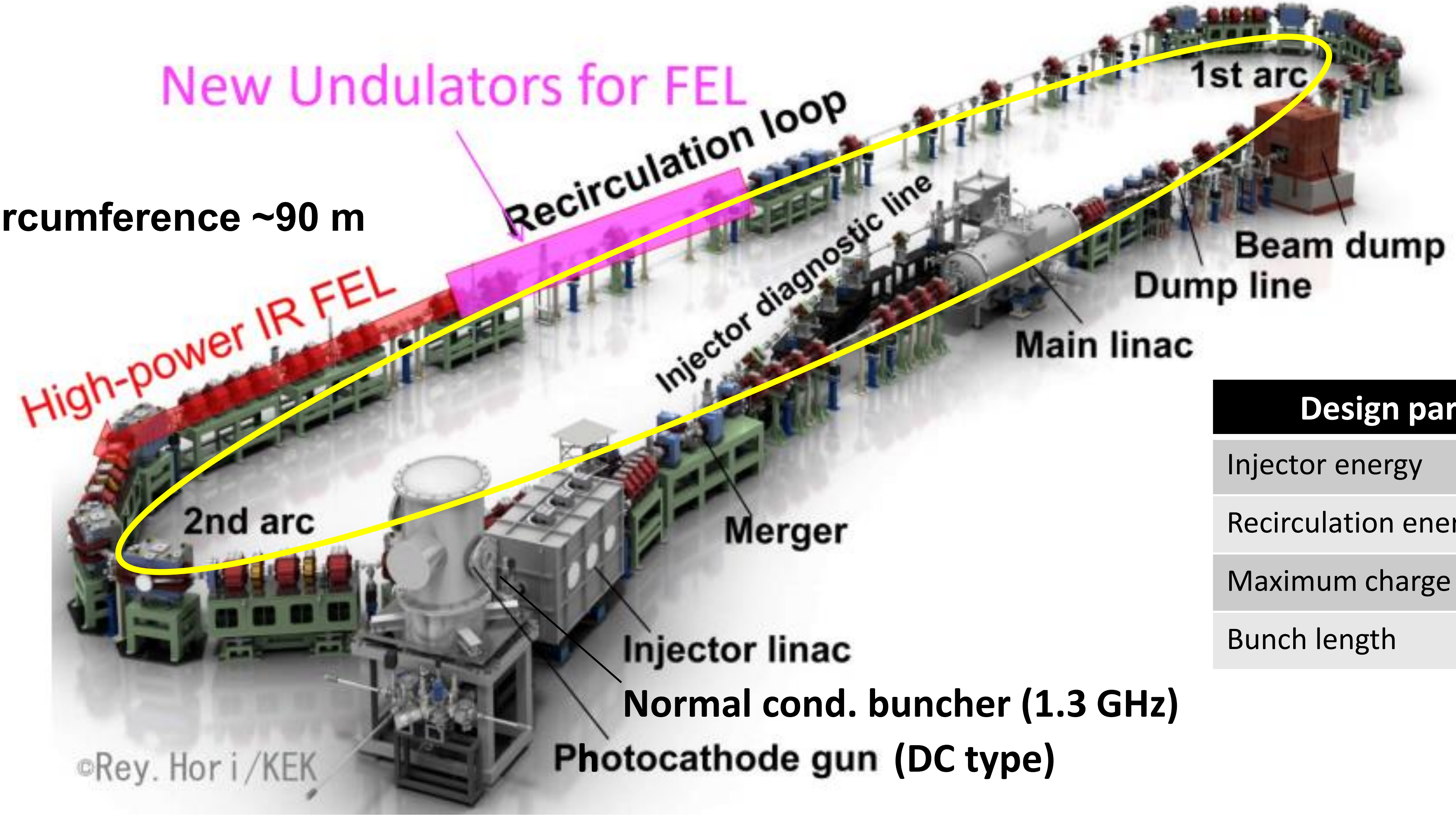

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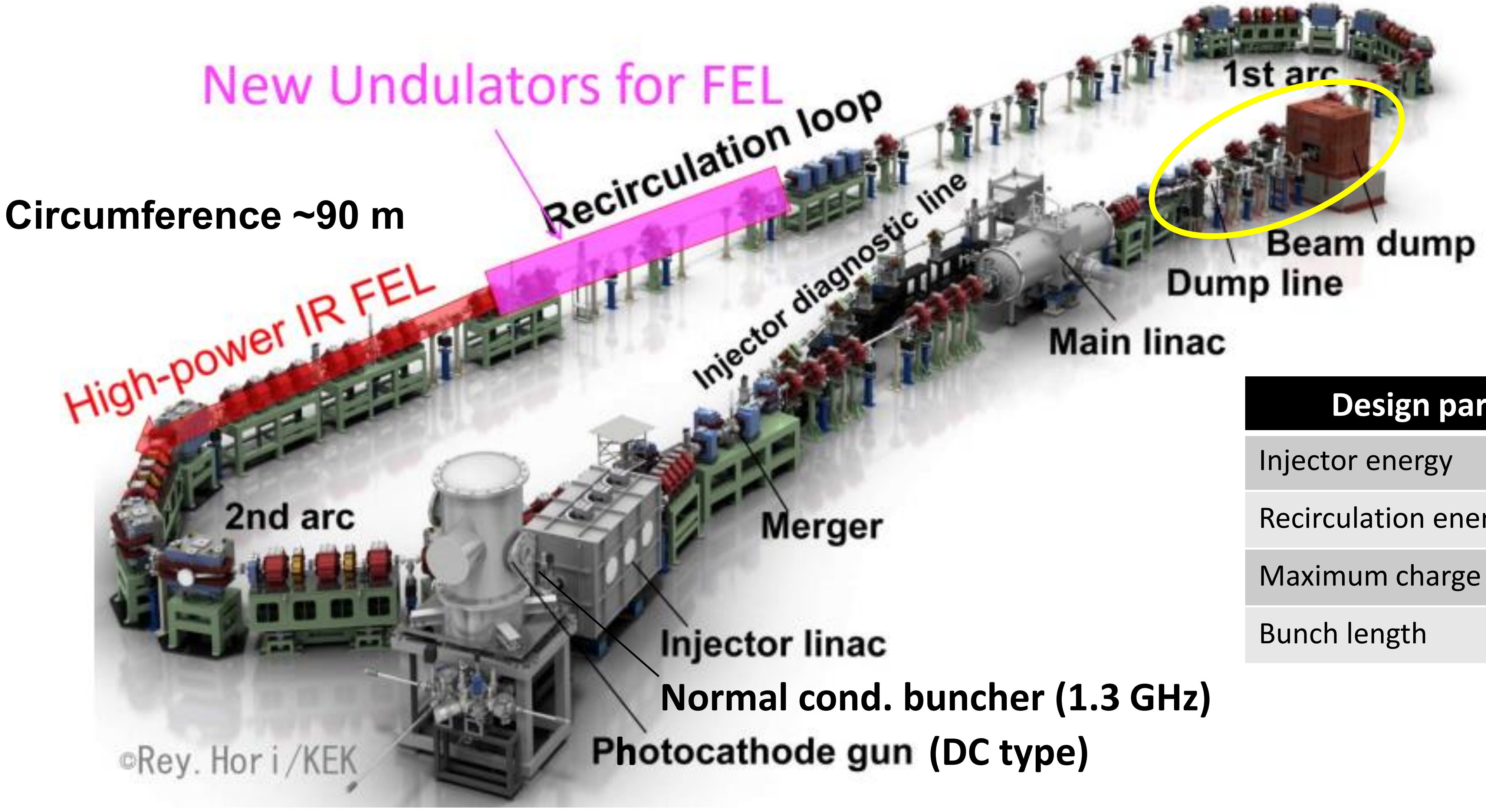

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Introduction
cERL operation highlights since restart at 2017

- 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 with recirculation loop energy 17.6 MeV. **World record:** Stable DC photocathode gun operation with 500 kV and CW 1 mA for 2 hours.
- June, October 2019: High bunch charge operation (max. 60 pC/bunch) toward IR-FEL test. CW beam operation (< 10 μA).
- March 2020: FEL operation with U1 (max. 60 pC/bunch) for FEL tuning.
- June 2020: FEL operation with U1&U2 (max. 60 pC/bunch) for FEL tuning.
- February – March 2021: FEL operation with U1&U2 (max. 60 pC/bunch) for FEL light production.

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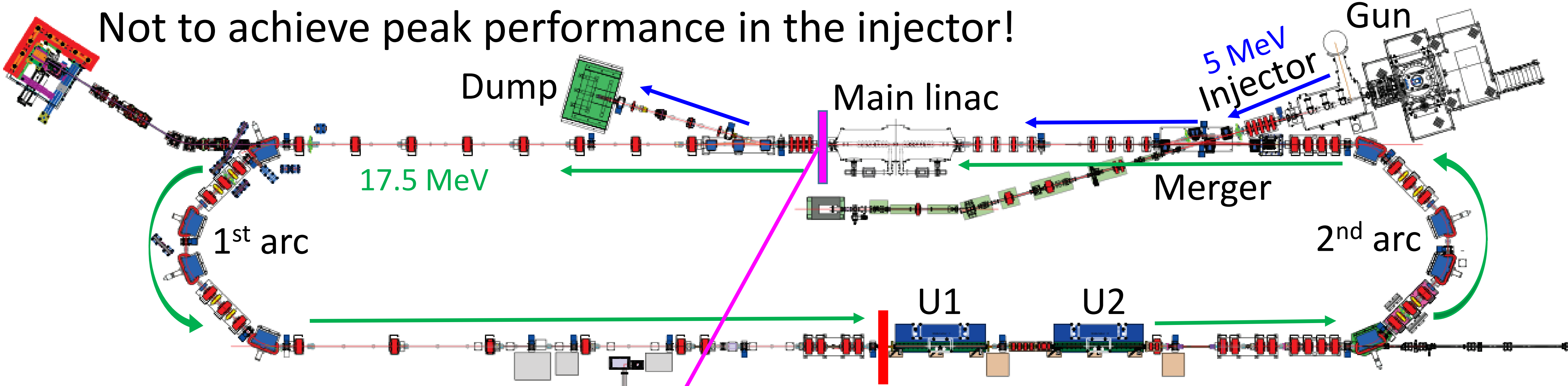
Injector optimization

Targets

- <u>Main goal</u>: 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!



- <u>Target beam performance at the Main linac exit:</u>
  - 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

- <u>Required beam performance at the U1:</u>
  - 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

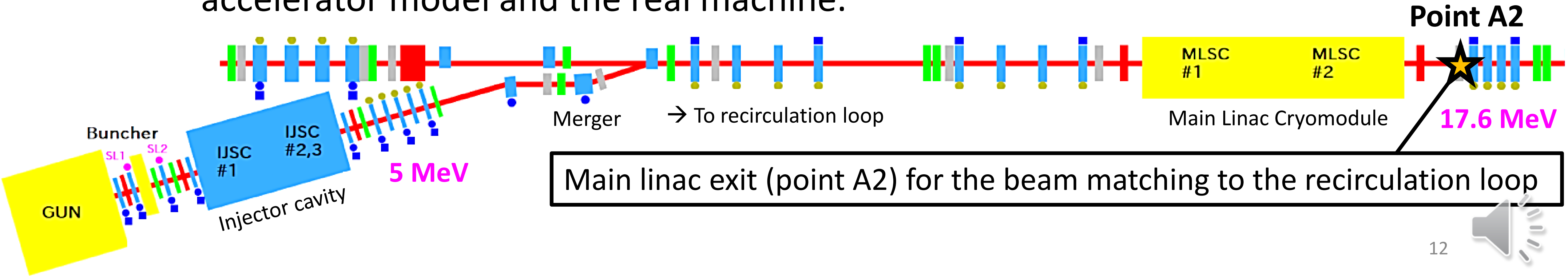
Challenges in Jun. 2020 vs Feb.–Mar. 2021

- 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
Initial laser dist.	40 ps FWHM single Gaussian	40 ps FWHM flat-top

Injector optimization
Important remarks

- Why **matching point** (point A2) for the injector part into the recirculation loop is after the main linac (not at the end of the injector)?
  - Since the influence of the space charge effect is smaller at the recirculation energy of 17.6 MeV (note, injector energy is 5 MeV).
- Why confirmation of **particle distribution** at point A2?
  - It is to allow a consistent S2E simulation. Different components of the cERL are simulated in different codes (e.g. GPT, ELEGANT, Genesis, etc.) Than better distribution at the beginning of the tracking than smaller the gap between the accelerator model and the real machine.

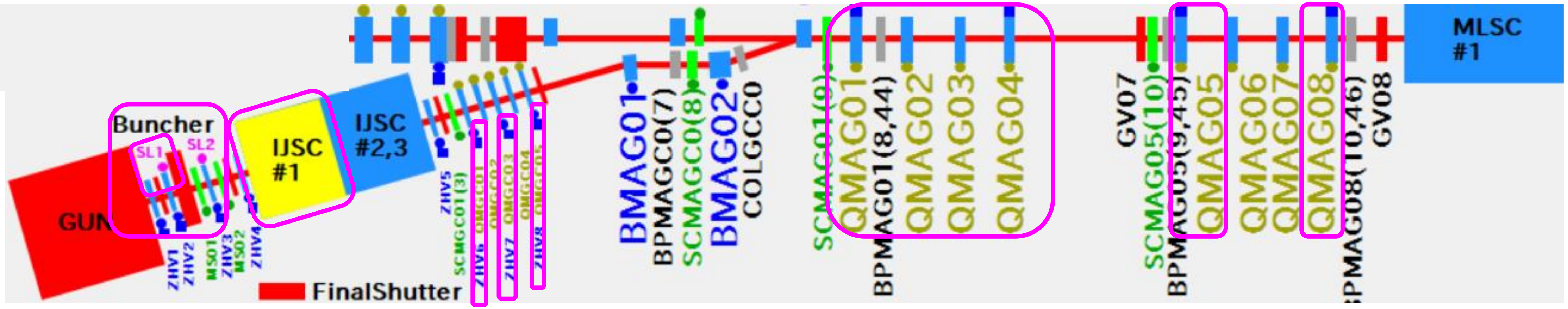


Injector optimization
Setup

- 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 $\beta_x < 8.0$ m; $\beta_y < 20.0$ m
Alpha function $-2.0 < \alpha_x < 0.0$; $-0.5 < \alpha_y < 0.5$

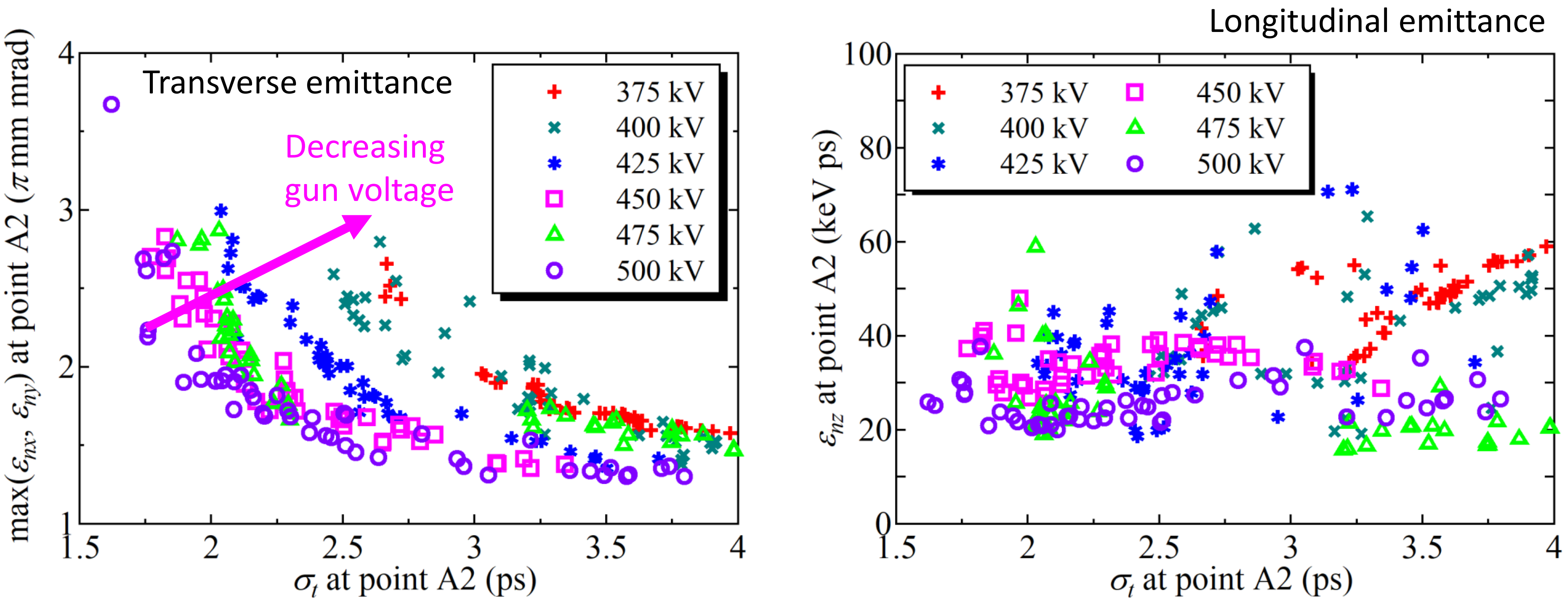
- Optimization parameters of MOGA (13 variables) are shown in magenta in the lattice below.



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.

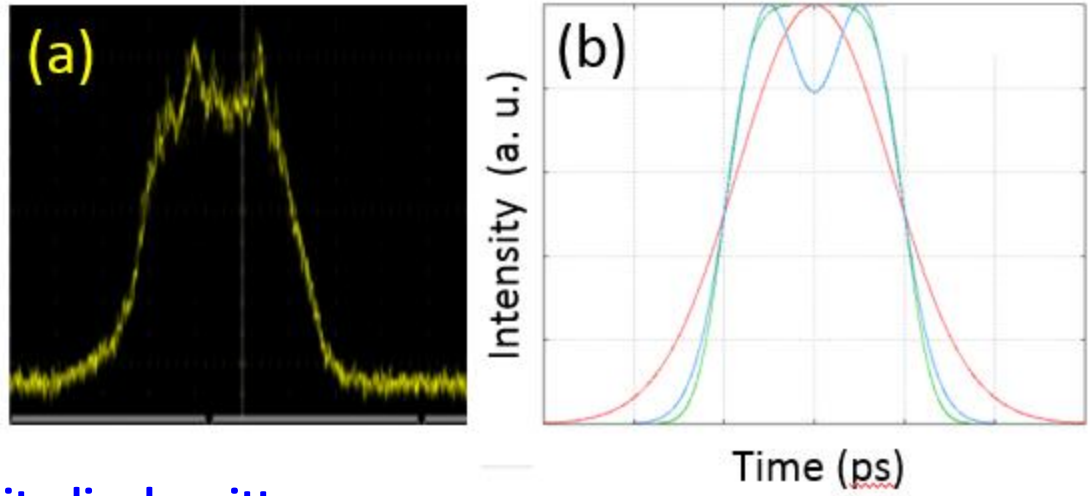


Injector optimization

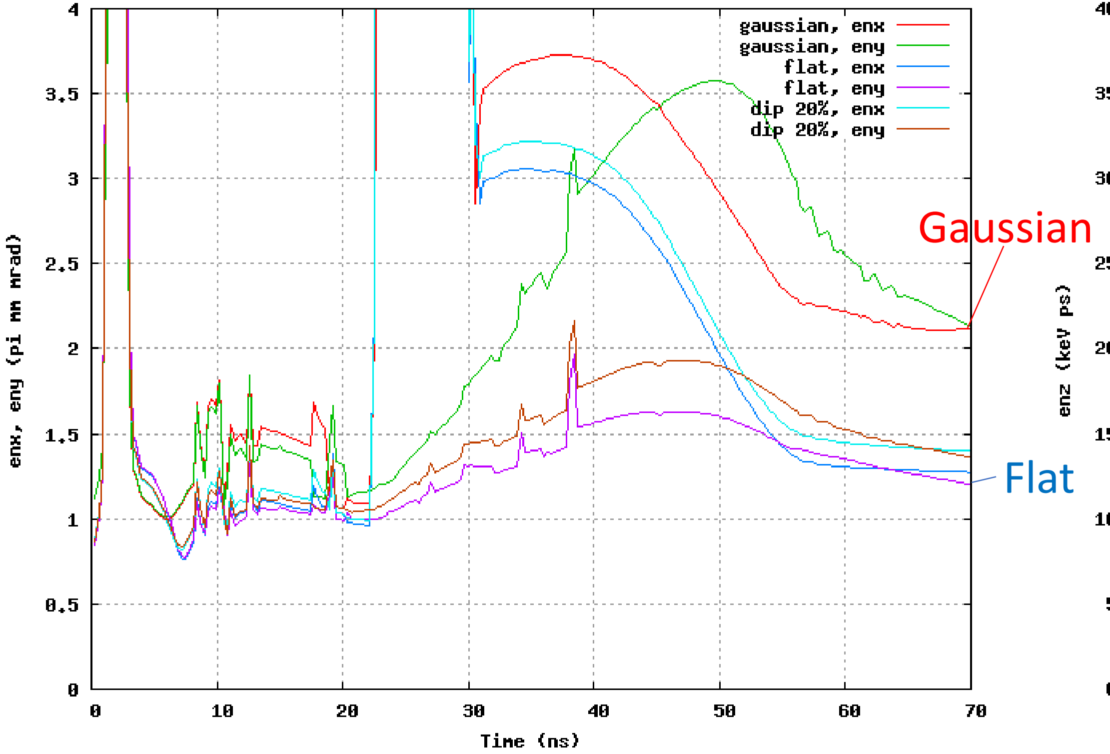
Effect of initial laser time distribution

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

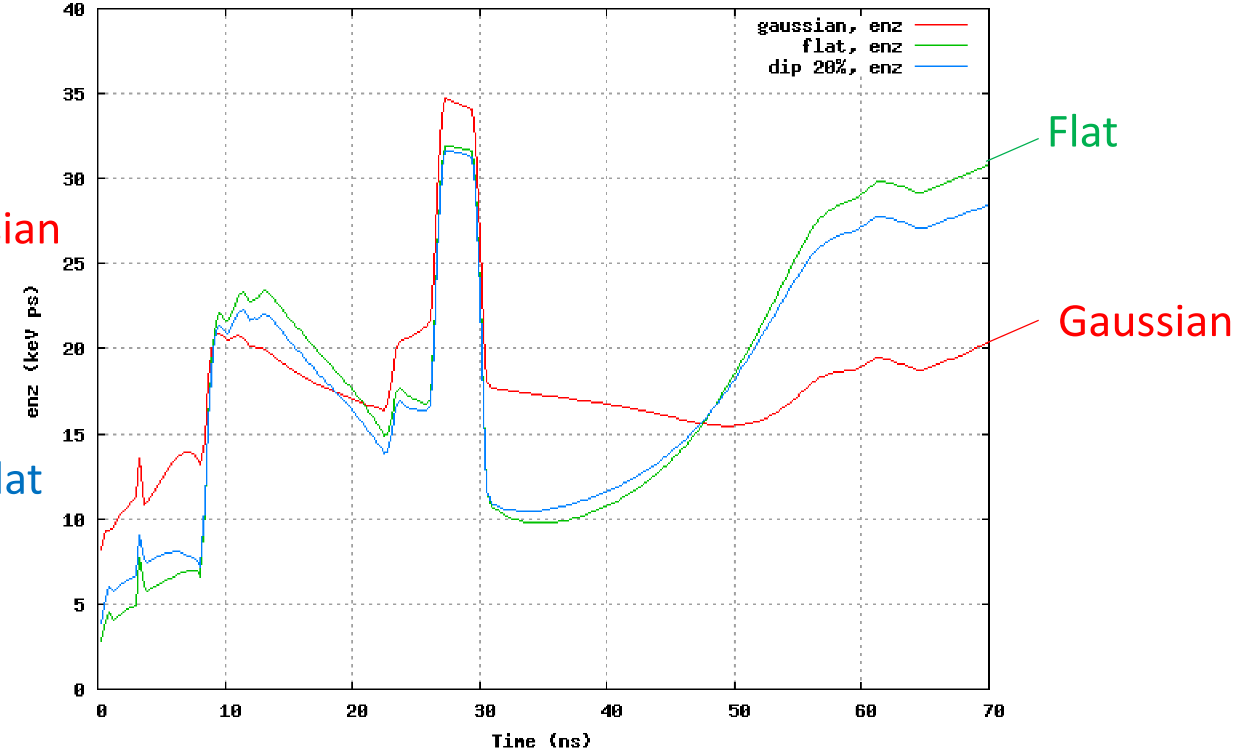
Real laser pulse

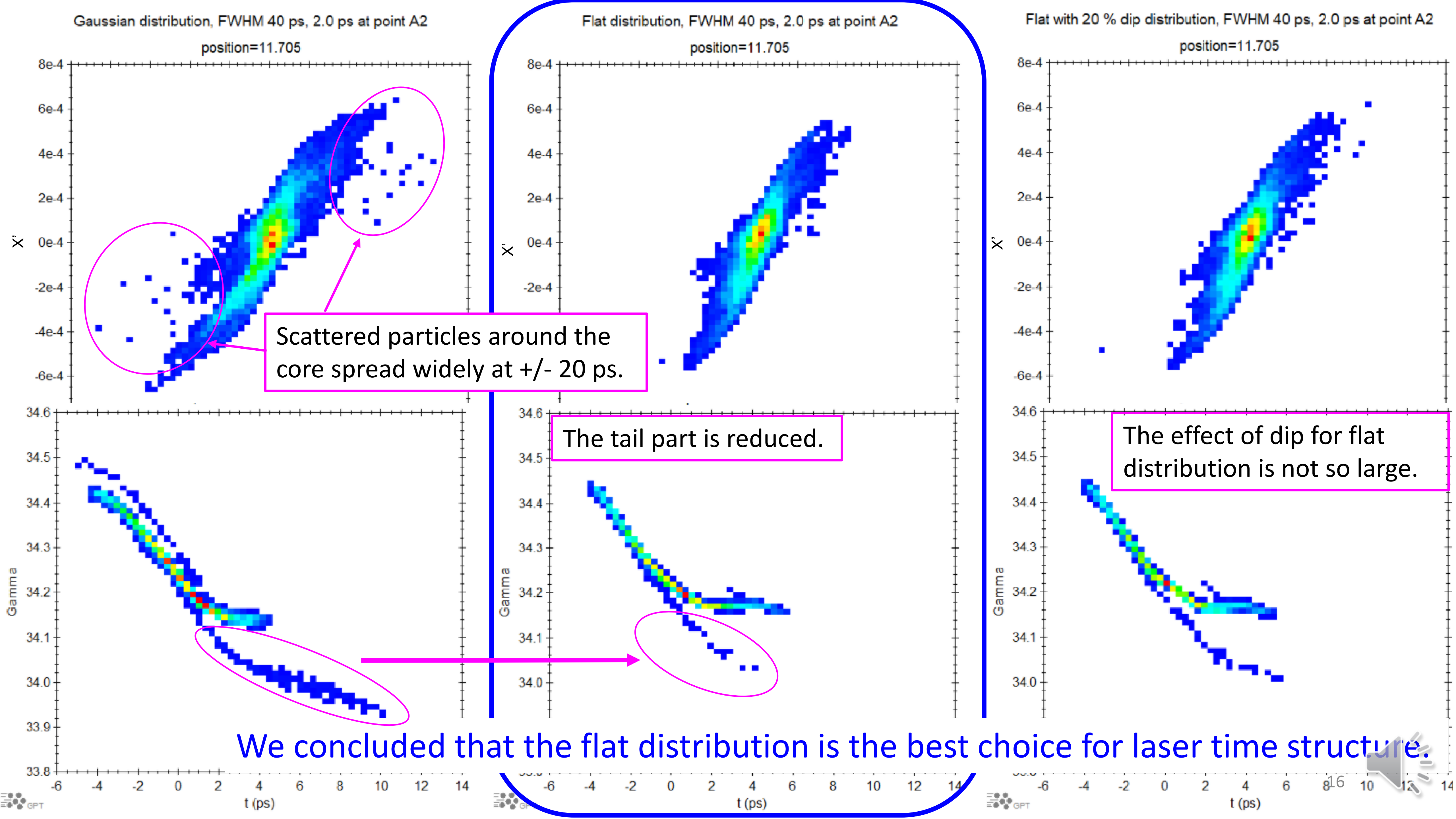


Transverse emittance



Longitudinal emittance





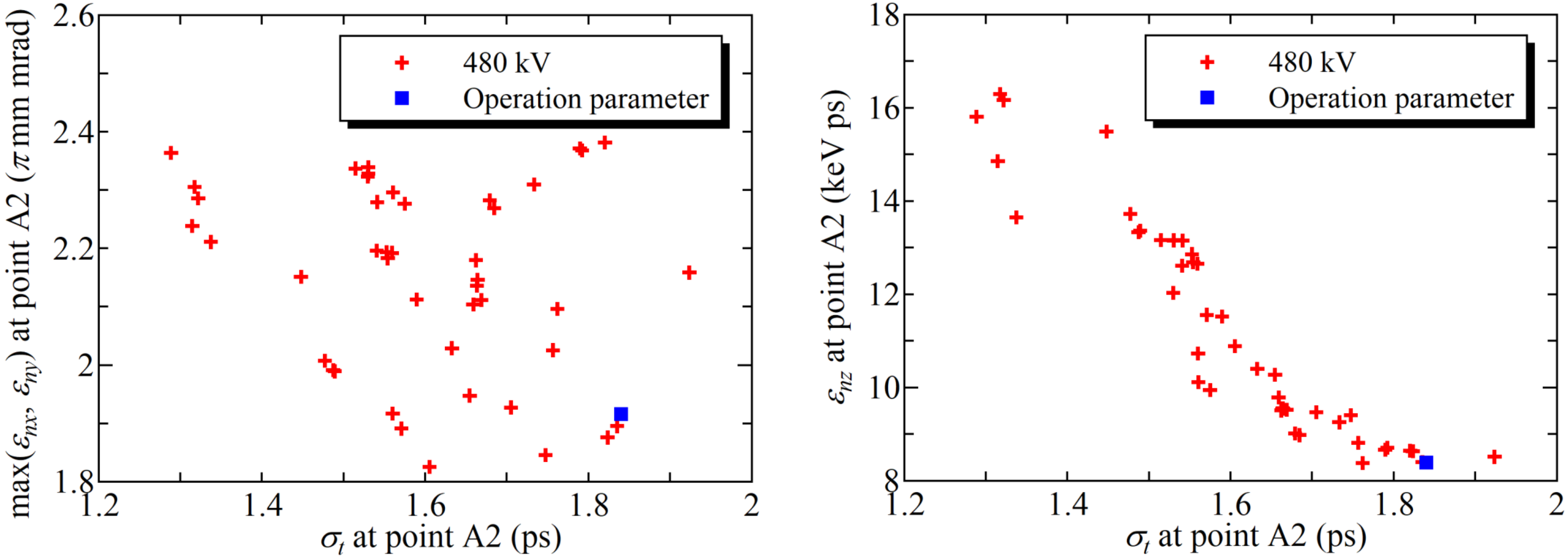
We concluded that the flat distribution is the best choice for laser time structure.

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**



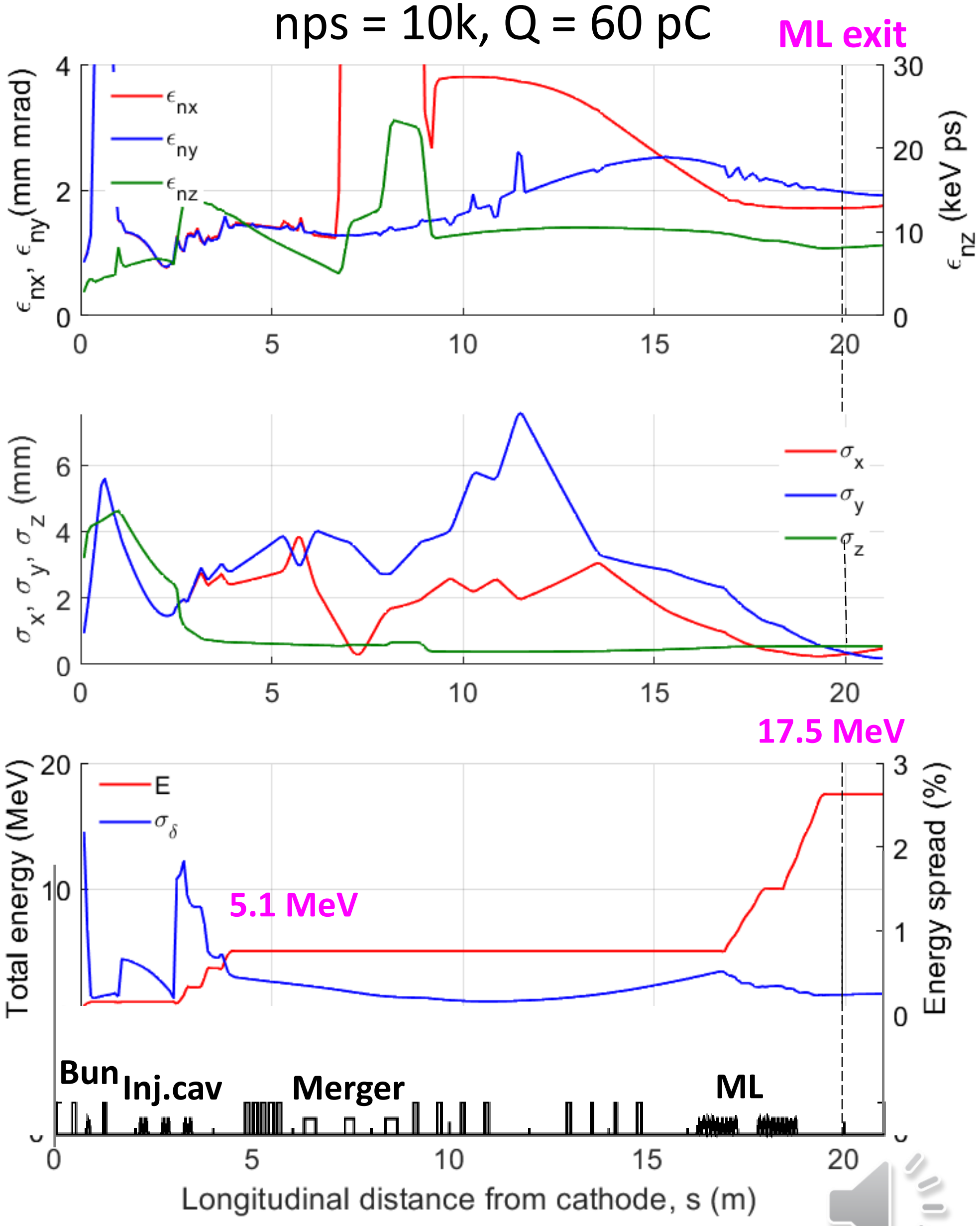
Injector optimization

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



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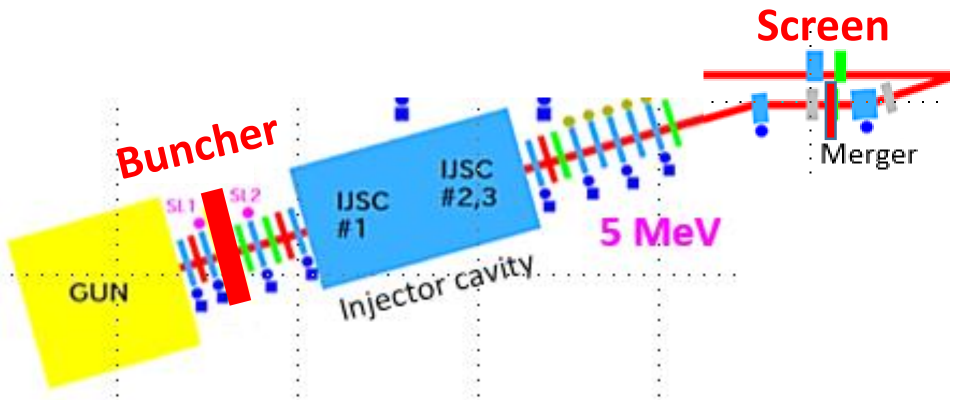
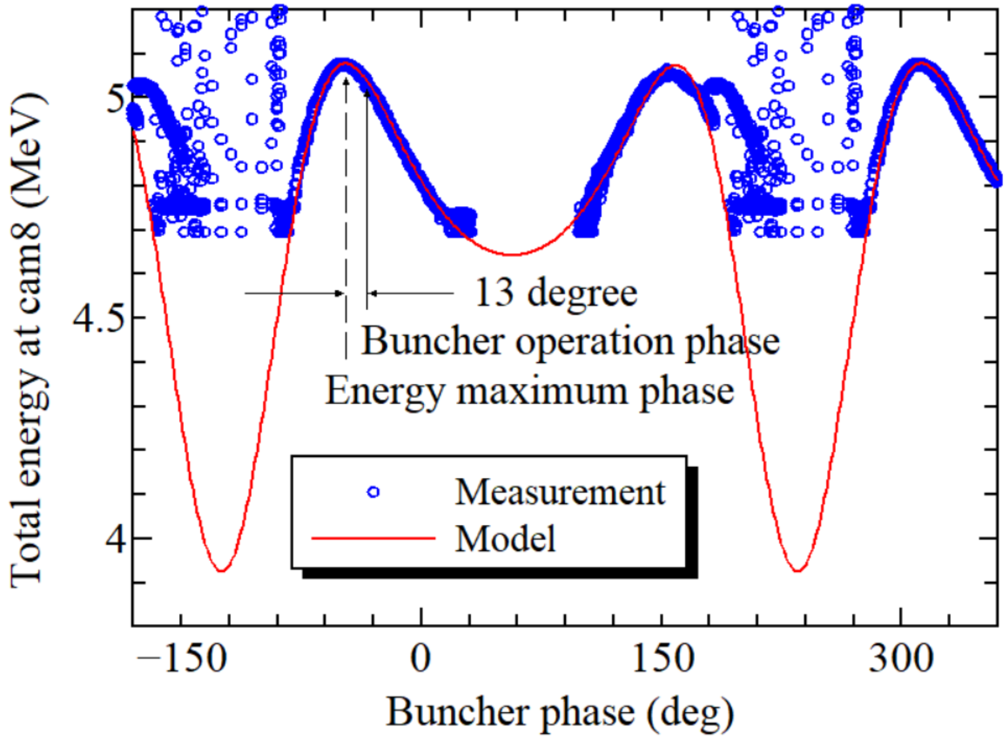
Comparison of the designed performance and measured results

Buncher tuning

- Remind: The goal for injector is to generate and to transport appropriate beam to the undulator entrance for IR-FEL light production.
- To adjust a single particle motion without space charge effect, we operated the injector with 1 pC bunch charge.



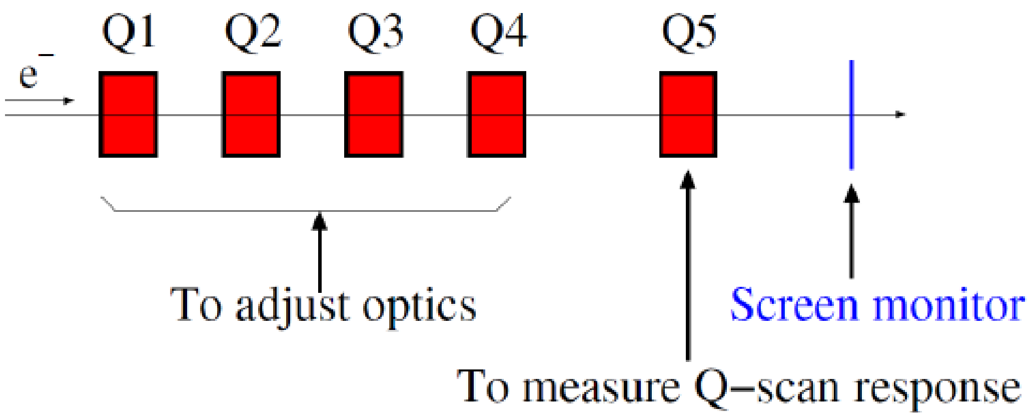


- In order to adjust longitudinal dynamics, we measured energy response to the buncher phase.
- The beam energy was measured on the screen in the merger section.
- After fine accelerator voltage and phase tunings, the measured response was almost consistent with the design response.

Comparison of the designed performance and measured results

Optics matching

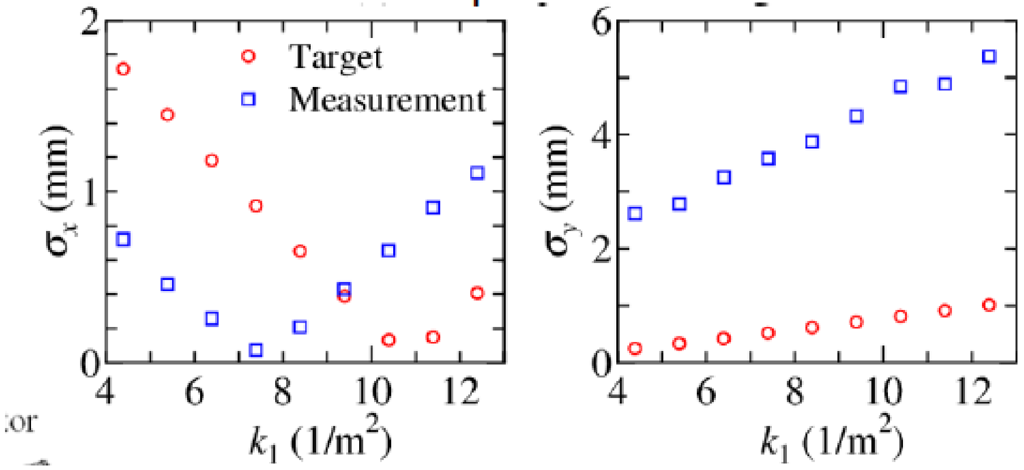
- To adjust multi particle motion including space charge effect, we measured quadrupole-scan (Q-scan) response.

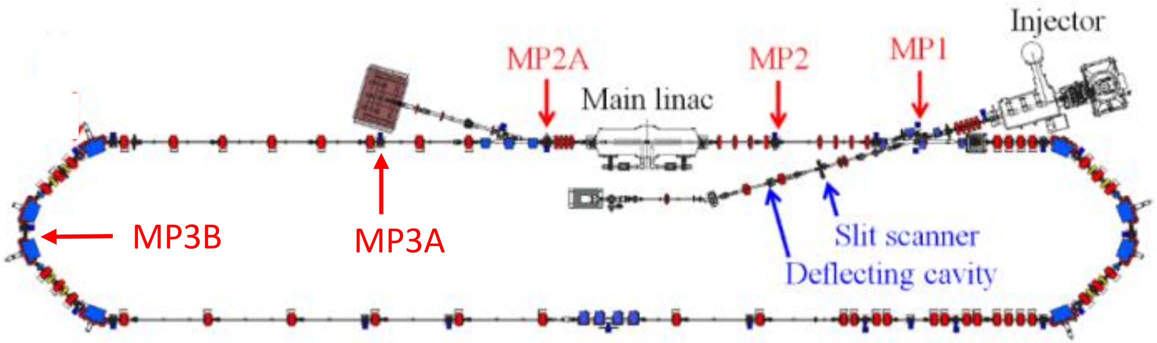


<u>Procedure of optics matching:</u>

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 correction values for four quadrupole magnets by solving the inverse measured response matrix.

Example of Q-scan





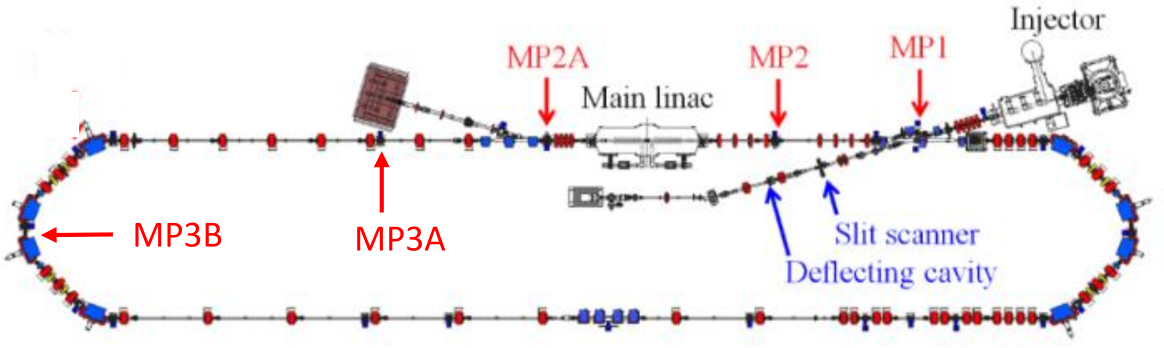
Optics matching points:

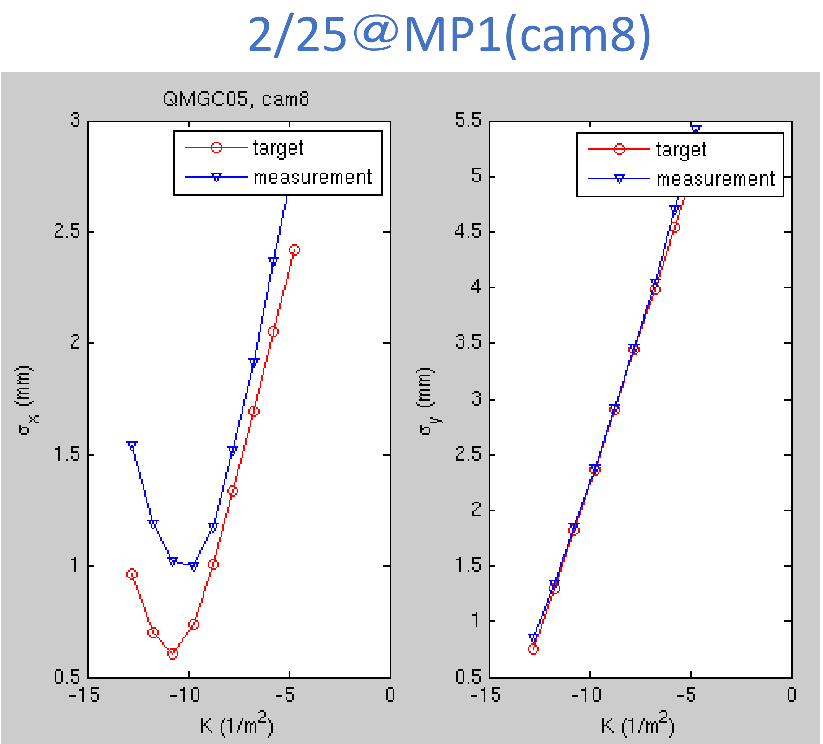
- For injector: MP1, MP2, MP2A
- For recirculation loop: MP3, MP3B

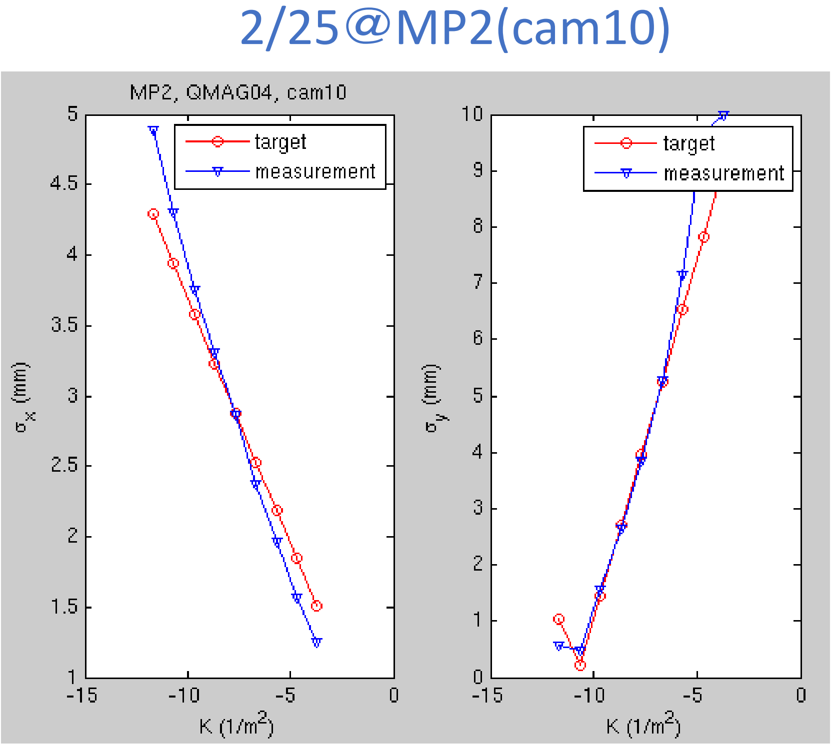
Comparison of the designed performance and measured results

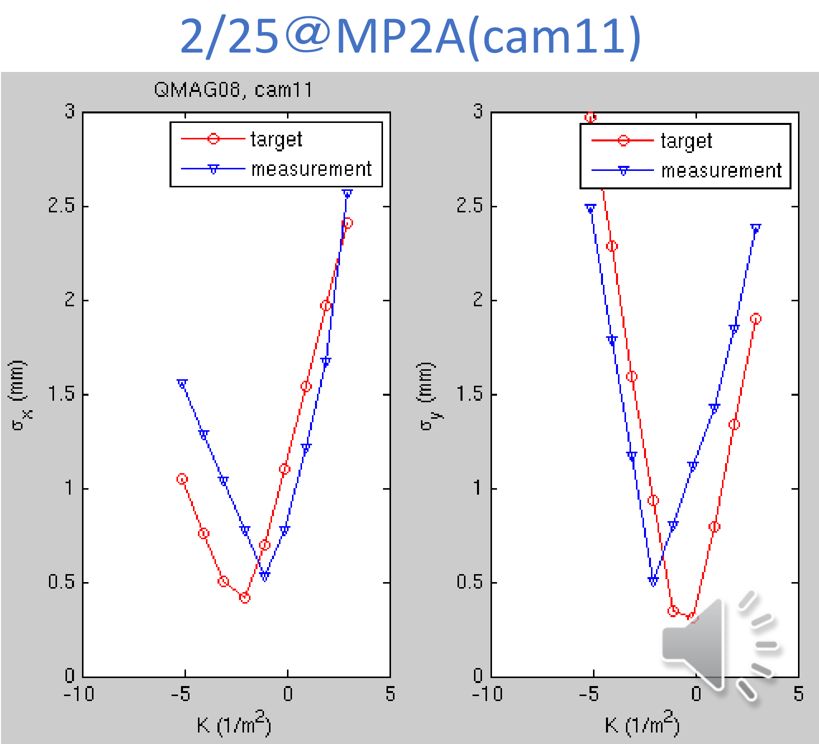
Optics matching result

- <u>Goal</u>: to connect the optics at each matching point (with space charge effect).
  - With our adjustment, the discrepancies became much smaller than the initial state.
  - Although small discrepancies still remain since the real emittances may differ from design values.



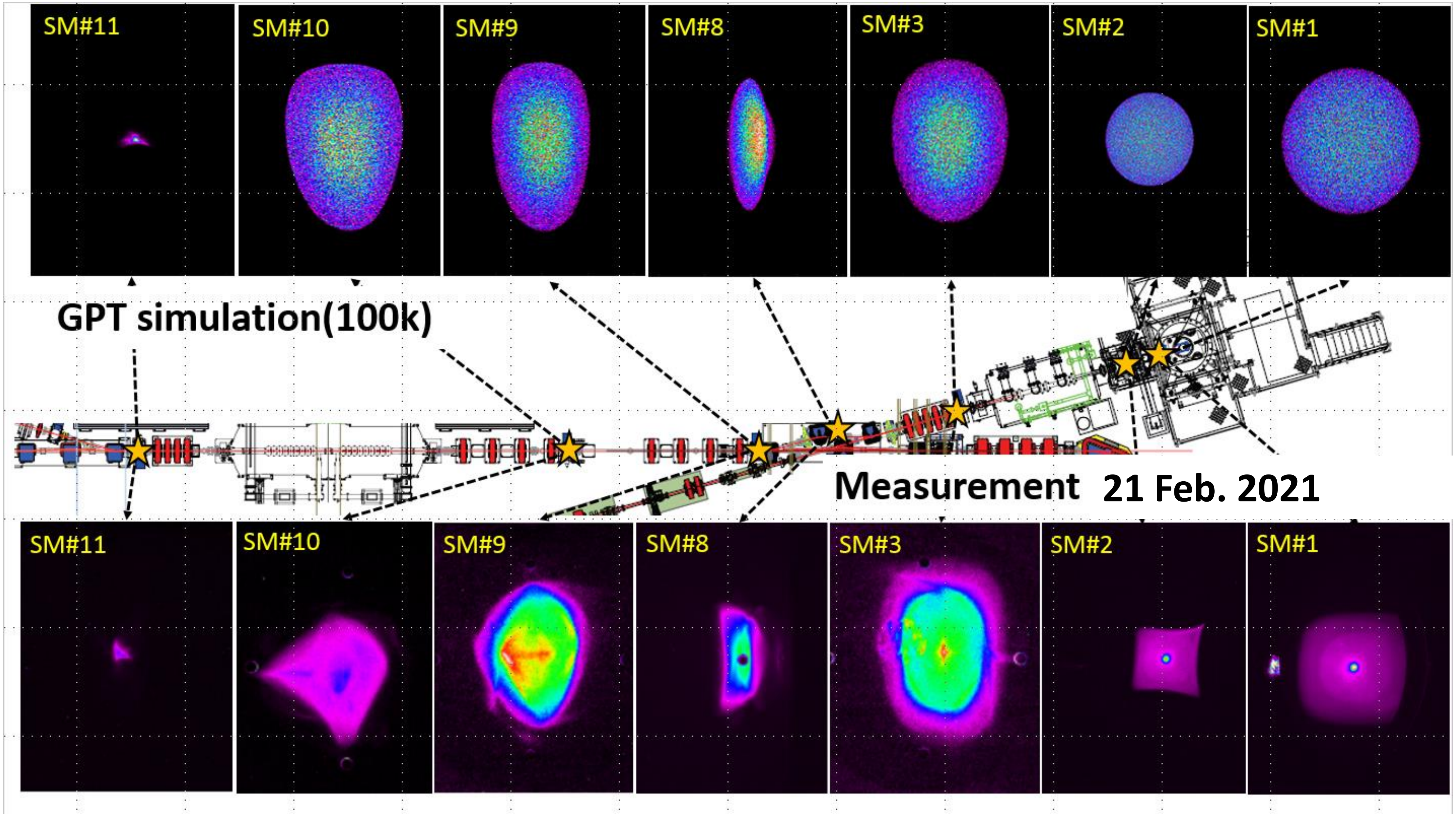






Beam profiles after optics tuning

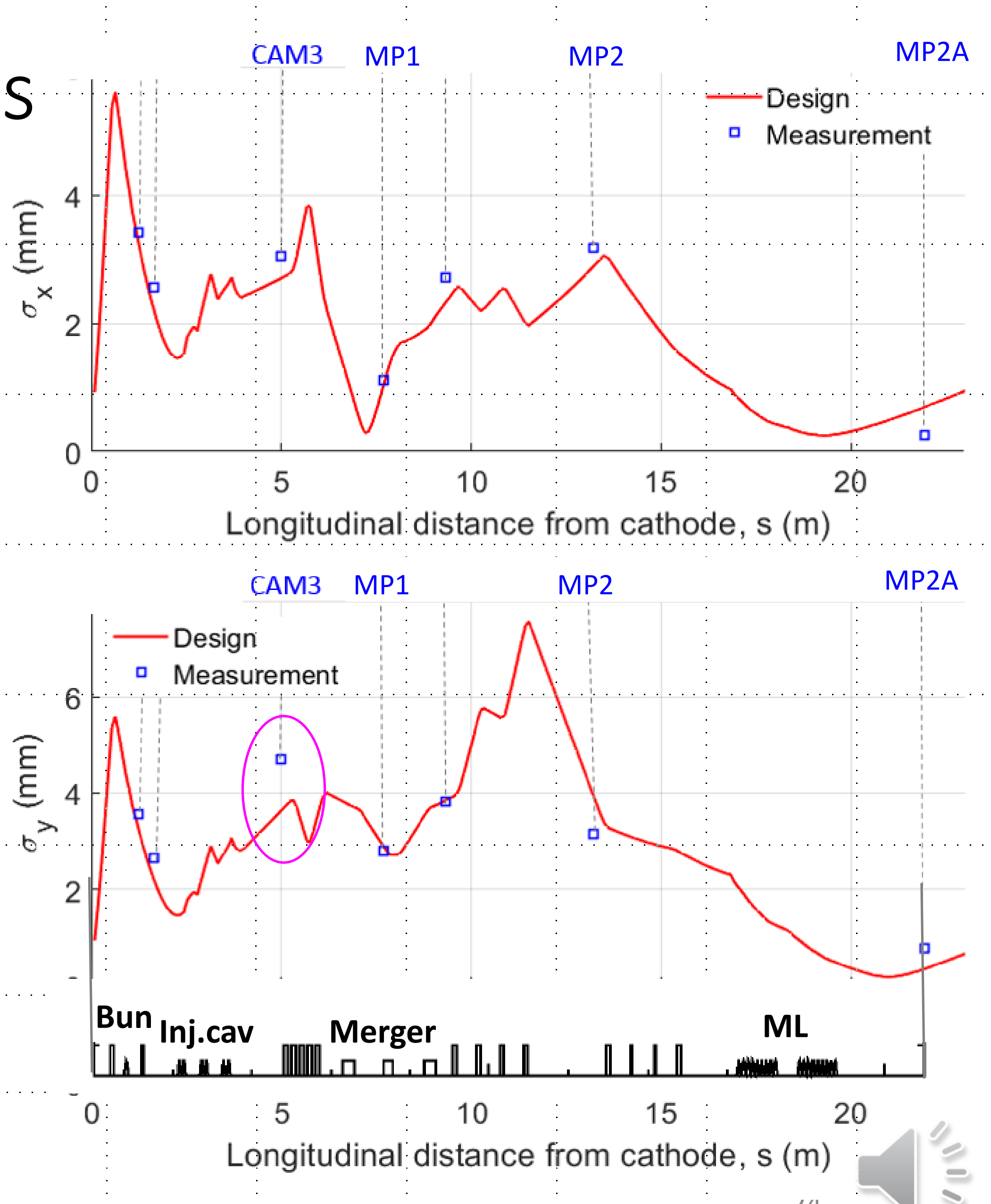
Note! Scales of simulation and actual measurement were matched



Comparison of the designed performance and measured results

Measured beam sizes

- The measured beam sizes well agreed with the design beam sizes except for the exit of injector.
- The reason for the deviation of the vertical beam size at Cam3 still unclear.
- It is necessary to investigate the space charge effect including the time structure of the excitation laser.
- These issues are the next study topic.

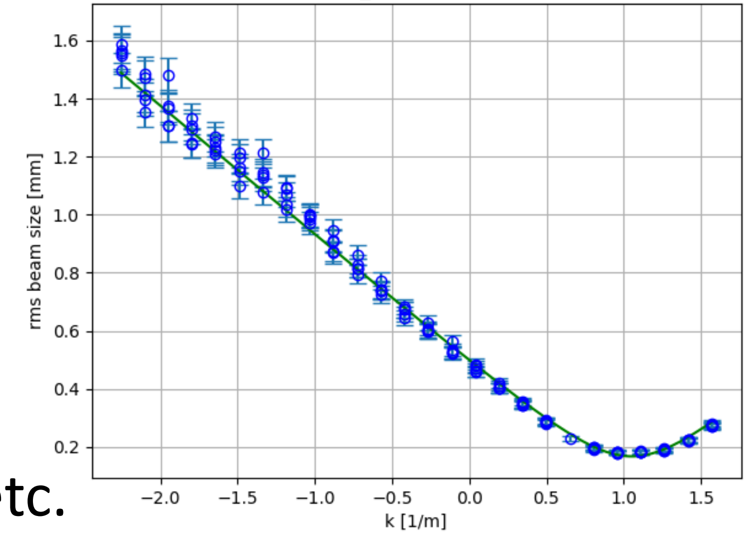


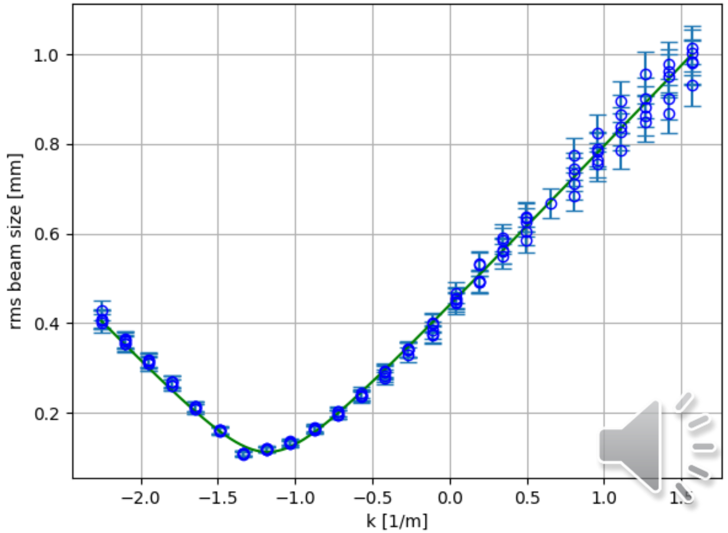
Comparison of the designed performance and measured results

Emittance for recirculation loop

- Feb. – Mar. 2021 emittance strategy: simultaneous minimization of the bunch length and the longitudinal emittance at point A2 (slightly different from cam11).
- Design values: **1.74 π mm mrad / 1.92 π mm mrad.**
- Measured values: **2.87 ± 0.03 π mm mrad / 1.57 ± 0.02 π mm mrad**
  - The measured vertical emittance is in a good agreement with the design value.
  - The difference in horizontal emittances still remains.
- Possible reasons:
  - The effect of the dispersion;
  - The phase offset of the laser;
  - Unwanted offsets of phases of the buncher, injector cavities etc.

From Q-scan result at matching point MP2A, we calculate transverse emittance.





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 produced IR-FEL light at the beam energy 17.6 MeV (refer to R. Kato's poster TUPAB099).
- 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.

IPAC’21 presentations about cERL operation

1. D. Naito “*Production and Performance Evaluation of a Compact Deflecting Cavity to Measure the Bunch Length in the cERL*” ID: 1564 - MOPAB330.
2. R. Kato “*Construction of an infrared FEL at the compact ERL*” ID: 2018 - TUPAB099.
3. N. Nakamura “*Specifications and Performance of a Chicane Magnet for the cERL IR-FEL*” ID: 2334 - TUPAB064.
4. Y. Honda “*Development of Terahertz Source Based on Coherent Diffraction Radiation at ERL Test Accelerator in KEK*” ID: 2359 - WEPAB076.

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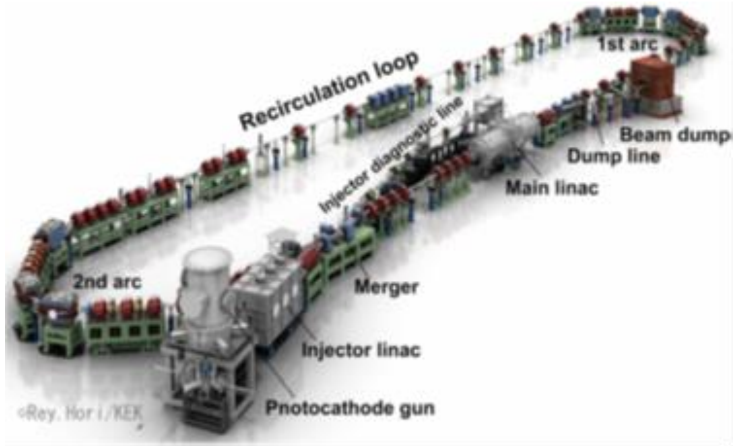

Thank you for your attention!