ERL 2024
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on Energy Recovery Linacs

WEO01

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Injector optics design and optimization for cERL

9:00 ~ 9:20, September 25, 2024, Kobayashi Hall

The 69th ICFA Advanced Beam Dynamics Workshop
on Energy Recovery Linacs (ERL2024)

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On behalf of cERL team

15+5 min
+ 18 pages

Outline

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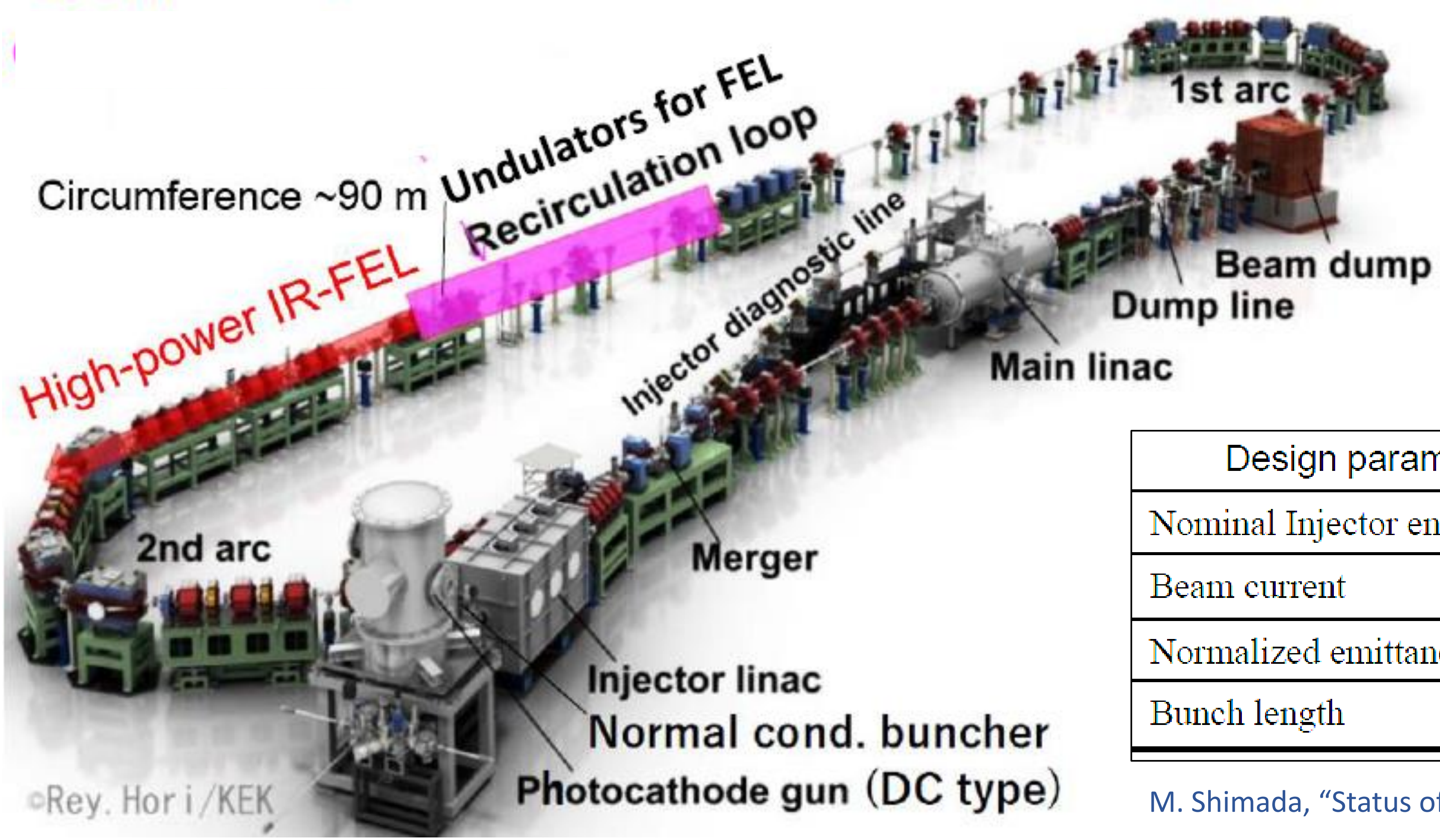
Introduction

Overview of the Injector of the Compact Energy Recovery Linac (cERL)

cERL's ongoing developments leverage innovative strategies to enhance performance of the injector system and achieve operational objectives across various modes.



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)

M. Shimada, "Status of cERL, this conference", TUO01

Introduction

Definition and Role of Injector Optics

The goal of electron injector optics is to produce a high-quality electron beam that meets the demands of subsequent acceleration and application processes.

- **Beam Quality:** Influences emittance, energy spread, and bunch length.
- **Initial Beam Parameters:** Establishes crucial conditions for downstream acceleration.
- **Acceleration Efficiency:** Maximizes transport efficiency, increasing output.
- **Space Charge Mitigation:** Reduces distortions and preserves beam quality.
- **Stability and Control:** Ensures precise control over beam parameters.
- **Compatibility:** Ensures seamless operation with downstream components.
- **Operational Flexibility:** Adapts to various modes (e.g., CW, pulsed).
- **R&D Opportunities:** Key area for innovations and performance enhancements.
- **Cost-Effectiveness:** Minimizes beam loss and operational costs.

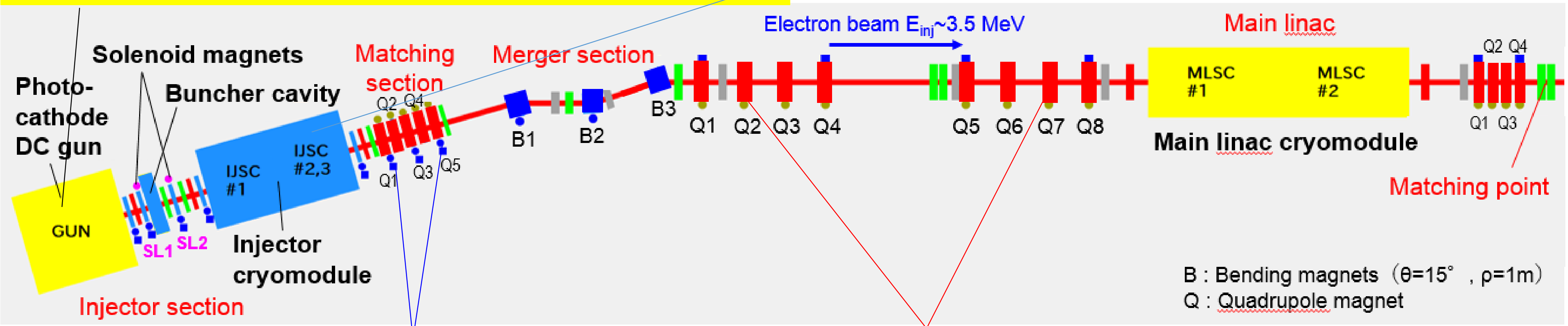
Injector Optics Overview

Key Components (e.g., guns, magnets, beam transport)

Electron injector optics refers to the design and configuration of components that shape and direct electron beams in an electron injector system. Key elements of electron injector optics include:

Beam Formation: Ensuring that the electron beam has the desired shape and size for optimal performance.

Energy Modulation: Adjusting the energy of the electrons to achieve specific acceleration requirements.



Beam Steering: Controlling the trajectory of the electrons to keep them aligned as they enter the accelerator.

Focusing Mechanisms: Using magnetic or electric fields to focus the beam, minimizing divergence and maximizing intensity.

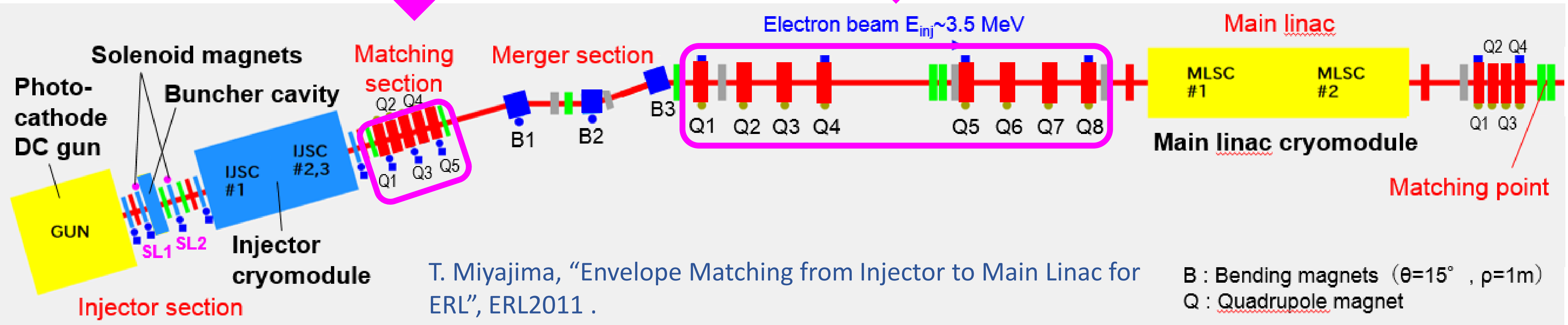
Injector Optics Overview

Purpose of Quadrupole Magnets

- **Does envelope matching compromise emittance minimization?**

Three-step optimization

- **5 quadrupole magnets before merger:**
  - To match the envelope at the exit of merger to minimize emittance growth caused by space charge and dispersion in merger section.
- **8 quadrupole magnets after merger:**
  - To adjust the envelope at the matching point.
  - To minimize emittance growth in the long straight section.



T. Miyajima, "Envelope Matching from Injector to Main Linac for ERL", ERL2011 .

B : Bending magnets（θ=15°　, ρ=1m）
Q : Quadrupole magnet

Design Challenges

Designing electron injector optics involves several challenges, including:

1. **Beam Quality:** Achieving the desired beam shape, size, and emittance to ensure high-quality injection.
2. **Alignment:** Maintaining precise alignment of components to prevent beam misdirection and degradation.
3. **Space Charge Effects:** Managing the repulsive forces between electrons in high-current beams, which can lead to instabilities.
4. **Magnetic Field Uniformity:** Ensuring consistent magnetic fields in quadrupole and solenoid magnets to avoid beam distortion.
5. **Energy Spread Control:** Minimizing variations in electron energy to enhance beam focus and performance.
6. **Beam Dynamics:** Understanding and optimizing the interplay between various forces acting on the beam during acceleration.
7. **Beam loss control:** Is achieved through the strategic placement of collimators, which effectively limit unwanted particle scattering and enhance overall beam stability.
8. **Etc. …**

M. Kurata, "Machine learning for high current beam operation at cERL", this conference, TUO12.

Design Parameters (I)

Initial parameters (6): are **initial conditions** decided by the **goal of the run** and they are **fixed.**

1. **Gun Voltage** Higher gun voltages typically result in higher energy electrons, leading to improved beam quality and reduced space charge effects. However, excessive voltage can lead to increased noise and instability.
2. **Injection Energy** Injection energy must be optimized to ensure effective acceleration and minimal losses during the initial phase. It influences the beam dynamics as electrons transition into higher-energy regimes.
3. **Pulse Duration** Shorter pulse durations can lead to higher peak currents but require careful management to avoid overheating and other stability issues.
4. **Initial Beam Size and Shape** The size and shape of the beam affect its interaction with subsequent accelerator components and the overall efficiency of the acceleration process.

Target parameters (8): are **parameters** to be **optimized**.

1. **Emittance** Low emittance is crucial for maintaining beam focus and quality. It is influenced by factors such as the electron gun design and the space charge effects in the injector.
2. **Current** Higher current can enhance beam brightness but also leads to space charge effects that can degrade beam quality. Balancing current is essential for optimal performance.
3. **Final Beam Size and Shape** (at the matching point) The size and shape of the beam affect its interaction with subsequent accelerator components and the overall efficiency of the acceleration process.
4. **Energy Spread** A narrow energy spread is critical for maintaining coherence and stability in the accelerator. High energy spread can lead to beam instabilities and reduced performance.

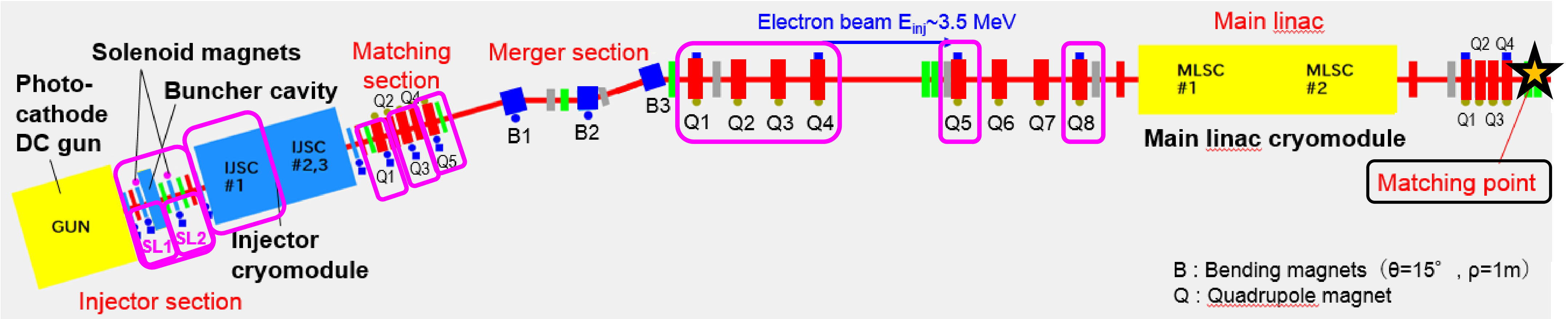
O.A. Tanaka, T. Miyajima, and T. Tanikawa, “Present Status of the Injector at the Compact ERL at KEK”, in Proc. IPAC'22, Bangkok, Thailand, Jun. 2022, pp. 2296-2298. doi:10.18429/JACoW-IPAC2022-WEPOMS024

Design Parameters (II)

Variables (decisions of optimization, 14 variables)

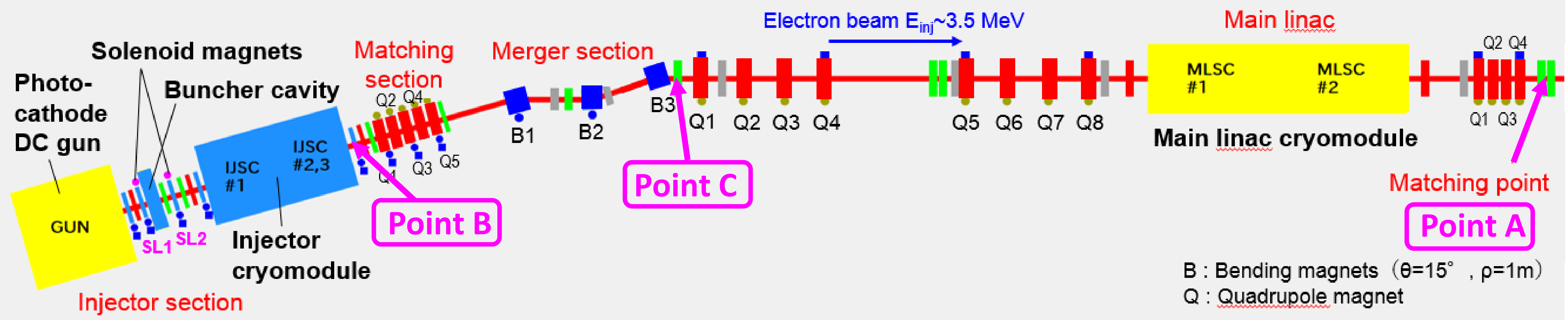
1. **Solenoid's current** plays a vital role in the optimization of electron injectors by influencing beam focusing, stability, aberration correction, energy modulation, and space charge management.
2. The **voltage of the buncher cavity** influences bunch compression, energy modulation, beam quality, stability, and the management of space charge effects.
3. The **voltage of the injector cavity** influences energy gain, beam quality, bunch compression, stability, and space charge management.
4. The **phase offset of an injector cavity** influences phase synchronization, beam quality, bunch compression, stability, and space charge management.
5. The **strength of quadrupole magnets** impacts beam focusing, stability, emittance management, space charge mitigation, and injection efficiency.

Variables	Vary from … to …
Solenoid 1&2 currents	5 ~ 12 A
Buncher voltage	30 ~100 kV
Inj. cavities accl. field	2 ~ 6.5 MV/m
Inj. Cavity 1 phase offset	-45 ~ 10 deg.
Straight of quad. MQ1	0 ~ 25 1/m^2
Straight of quad. MQ3	-25 ~ 0 1/m^2
Straight of quad. MQ5	0 ~ 25 1/m^2
Straight of quad. SQ1	-25 ~ 0 1/m^2
Straight of quad. SQ2	0 ~ 25 1/m^2
Straight of quad. SQ3	-25 ~ 0 1/m^2
Straight of quad. SQ4	0 ~ 25 1/m^2
Straight of quad. SQ5	-25 ~ 0 1/m^2
Straight of quad. SQ8	0~ 25 1/m^2



Modeling Approach/Optimization Techniques

- **Optimization method:** the beamline parameters form the gun to the matching point were optimized using "multi objective genetic algorithm (MOGA)".
- **Tracking code:** General Particle Tracer (GPT) with mesh based 3D space charge calculation. Pulsar Physics, http://www.pulsar.nl/gpt/index.html
- **Optimization:**
  - **Step 1.** Minimize emittance and bunch length at **point B**.
  - **Step 2.** Minimize emittance at the exit of the merger **(point C)**, to estimate emittance growth in the merger.
  - **Step 3.** Minimize emittance at **point A**, (emittance compensation and envelope matching). T. Miyajima, "Envelope Matching from Injector to Main Linac for ERL", ERL2011 .



Case Studies/Examples

FEL Mode, Energy Recovery Mode, Continuous Wave Mode

	Single-pass FEL FY 2020	Recirculation mode FY 2021	CW mode FY2023
DC gun voltage	500 kV	390 kV	450 kV
Repetition rate	1.3 GHz	1.3 GHz	1.3 GHz
Injector energy	5 MeV	3.5 MeV	2.9 MeV
Recirculation energy	17.5 MeV	17.5 MeV	17.4 MeV
Charge per bunch	60 pC	40 pC	0.77 pC
Rms bunch length	2 ps	3.5 ps	< 2 ps
Norm. rms transverse emittance	< 3π mm mrad	< 3π mm mrad	< 1π mm mrad
Laser temporal distribution (FWHM)	FWHM 40 ps single Gaussian	FWHM 40 ps single Gaussian	Continuous wave
Laser XY distribution	Radial Gaussian + 2 mm pinhole	Radial Gaussian + 2 mm pinhole	Radial Gaussian + 0.5 mm pinhole

Experimental Validation

Model-Based Injector Tuning

- **Goal: Generate and transport an appropriate beam to the matching point.**
- **Typical Procedure:** Accelerate a 1 pC beam from 3.5 to 17.5 MeV. Transport beam to the matching point near design conditions.
- **Tuning Steps:**
  1. **Alignment:** Align simulated responses of solenoids with actual measurements at the downstream screen.
  2. **Energy Tuning:** Adjust phases and amplitudes of buncher and injector cavities (1-3). Measure energy response to buncher phase.
  3. **Quadrupole-Scan Measurement:** Use measured response matrix to calculate correction values for quadrupole magnets. Correct responses at each matching point.
  4. **Beam Size Measurement:** Measure beam size at each screen up to the main linac exit. Compare measured sizes to design values.

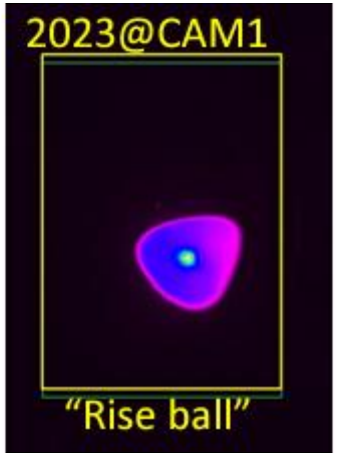
Injector tuning involves precise adjustments and measurements to optimize beam quality and performance in alignment with design expectations. Further matching procedures are under development to address discrepancies.

O.A. Tanaka, N. Higashi, and T. Miyajima, “Injector Optimization for the IR-FEL Operation at the Compact ERL at KEK”, in Proc. IPAC'21, Campinas, SP, Brazil, May 2021, pp. 4531-4534. doi:10.18429/JACoW-IPAC2021-FRXB07

Results and Discussion (I)

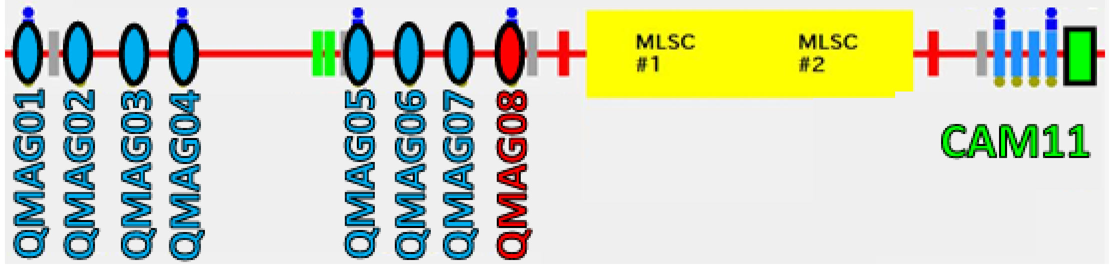
Operation mode	Single-pass FEL FY 2020		Recirculation mode FY2021		CW mode FY2023	
Beam parameters	**Model**	**Operation**	**Model**	**Operation**	**Model**	**Operation**
Horizontal beam size [mm]	0.58	0.44	0.59	0.57	0.27	0.18
Vertical beam size [mm]	0.50	0.78	0.43	0.49	0.22	0.58
Energy spread [%]	0.25	-	0.33	-	0.17	-
Bunch length [ps]	1.8	-	4.9	5.0	1.2	-
Horizontal emittance [π mm mrad]	1.95	1.46	3.54	6.00	0.69	0.39
Vertical emittance [π mm mrad]	1.74	2.23	2.04	3.87	0.44	0.48
Long. emittance [keV ps]	8.4	-	23.98	-	1.59	-
Alpha x	-1.52	-1.57	-0.28	-0.129	-0.32	0.16
Alpha y	-3.46	-1.82	4.51	0.09	0.33	14.86
Beta x [m]	7.37	4.14	3.38	1.51	4.36	0.41
Beta y [m]	2.04	1.26	3.19	3.79	4.69	5.25

Results and Discussion (II)



- Modeling and tuning procedures were effectively established for various operational modes.
- Challenges at the injector include:
  - Time-consuming model preparation.
  - Discrepancies between the injector model and the actual injector.
  - Optics inconsistencies.
  - Issues related to the triangular beam.

- MP2A：QMAG04～07/match. QMAG08 for scan



M. Yamamoto, "Preparation of cERL DC-gun upgrade for 10mA CW beam operation", this conference, WEO13.

Future directions

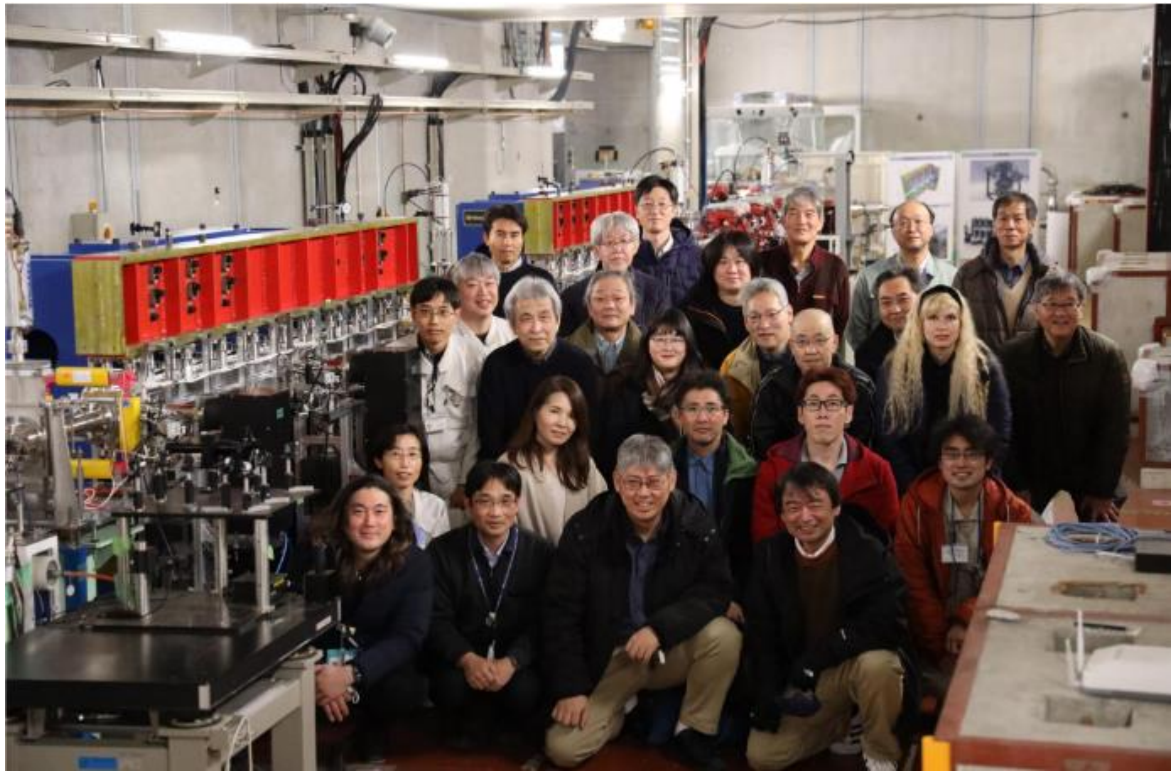
- ML for model construction and injector tuning.
- Deeper study of beam handling issues:
  - Triangle beam
  - Optics matching failures
- Preparations to High-current (10 mA) beam operation in Nov. – Dec. 2024. M. Yamamoto, “Preparation of cERL DC-gun upgrade for 10mA CW beam operation”, this conference, WEO13.
- Further FEL operation developments. T. Tanikawa, “Development of regenerative-amplifier FEL at the compact ERL”, this conference, THO09.

Conclusion

- Systematic injector studies were conducted for various operational modes.
- The experience gained from these multiple operations has informed updates to our current model preparation and beam tuning procedures.
- However, the existing method of optics matching during injector tuning, which relies on manual adjustments, is inadequate for achieving optimal injector performance.
- Therefore, more automated procedures should be implemented.
- Enhancing model accuracy is essential to bridge the gap between simulated and real-world optics.

Thank you for your attention!

Acknowledgements



- I would like to extend my heartfelt gratitude to the Compact Energy Recovery Linac (cERL) team members for their invaluable support throughout my injector studies. Your expertise, dedication, and collaborative spirit have been instrumental in advancing my research.
- I appreciate the guidance and insights provided by each of you, which have greatly enhanced my understanding of the complexities involved in injector tuning. Thank you for creating an inspiring and supportive environment that fosters innovation and excellence. I look forward to continuing our work together and contributing to our shared goals.

Backup slides

Overview

Highlights

- Operates at KEK as a test accelerator for ERL technology development and applications.
- Active since 2017 for industrial application research.
- Two undulators installed in 2020 for high-power EUV-FEL light source development.

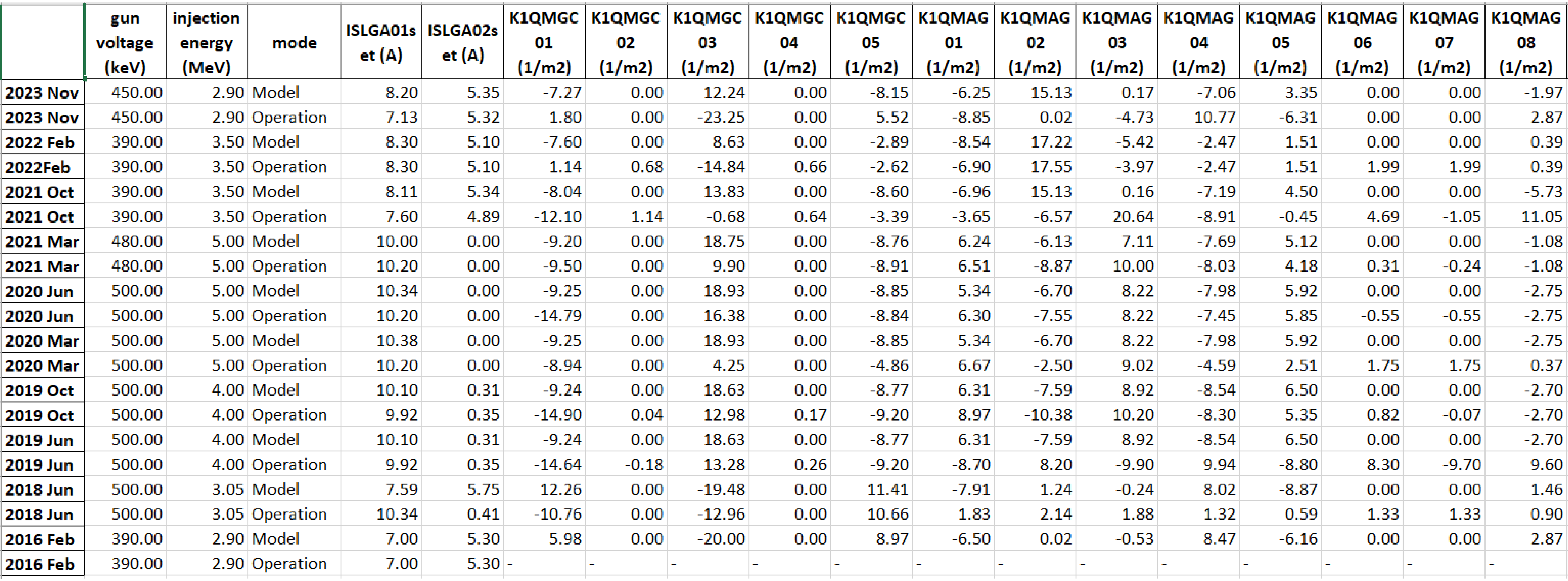
Actual Approaches

- Machine learning applied to optimize beam adjustment.
- Significant improvements in average beam current while minimizing beam loss.

Research

- Exploration of compatibility between FEL oscillation and energy recovery at 60 pC.
- Focus on strong space charge effects during operations.

Injector parameters for various operation modes



	gun voltage (keV)	injection energy (MeV)	mode	ISLGA01set (A)	ISLGA02set (A)	K1QMGC 01 (1/m2)	K1QMGC 02 (1/m2)	K1QMGC 03 (1/m2)	K1QMGC 04 (1/m2)	K1QMGC 05 (1/m2)	K1QMAG 01 (1/m2)	K1QMAG 02 (1/m2)	K1QMAG 03 (1/m2)	K1QMAG 04 (1/m2)	K1QMAG 05 (1/m2)	K1QMAG 06 (1/m2)	K1QMAG 07 (1/m2)	K1QMAG 08 (1/m2)
2023 Nov	450.00	2.90	Model	8.20	5.35	-7.27	0.00	12.24	0.00	-8.15	-6.25	15.13	0.17	-7.06	3.35	0.00	0.00	-1.97
2023 Nov	450.00	2.90	Operation	7.13	5.32	1.80	0.00	-23.25	0.00	5.52	-8.85	0.02	-4.73	10.77	-6.31	0.00	0.00	2.87
2022 Feb	390.00	3.50	Model	8.30	5.10	-7.60	0.00	8.63	0.00	-2.89	-8.54	17.22	-5.42	-2.47	1.51	0.00	0.00	0.39
2022Feb	390.00	3.50	Operation	8.30	5.10	1.14	0.68	-14.84	0.66	-2.62	-6.90	17.55	-3.97	-2.47	1.51	1.99	1.99	0.39
2021 Oct	390.00	3.50	Model	8.11	5.34	-8.04	0.00	13.83	0.00	-8.60	-6.96	15.13	0.16	-7.19	4.50	0.00	0.00	-5.73
2021 Oct	390.00	3.50	Operation	7.60	4.89	-12.10	1.14	-0.68	0.64	-3.39	-3.65	-6.57	20.64	-8.91	-0.45	4.69	-1.05	11.05
2021 Mar	480.00	5.00	Model	10.00	0.00	-9.20	0.00	18.75	0.00	-8.76	6.24	-6.13	7.11	-7.69	5.12	0.00	0.00	-1.08
2021 Mar	480.00	5.00	Operation	10.20	0.00	-9.50	0.00	9.90	0.00	-8.91	6.51	-8.87	10.00	-8.03	4.18	0.31	-0.24	-1.08
2020 Jun	500.00	5.00	Model	10.34	0.00	-9.25	0.00	18.93	0.00	-8.85	5.34	-6.70	8.22	-7.98	5.92	0.00	0.00	-2.75
2020 Jun	500.00	5.00	Operation	10.20	0.00	-14.79	0.00	16.38	0.00	-8.84	6.30	-7.55	8.22	-7.45	5.85	-0.55	-0.55	-2.75
2020 Mar	500.00	5.00	Model	10.38	0.00	-9.25	0.00	18.93	0.00	-8.85	5.34	-6.70	8.22	-7.98	5.92	0.00	0.00	-2.75
2020 Mar	500.00	5.00	Operation	10.20	0.00	-8.94	0.00	4.25	0.00	-4.86	6.67	-2.50	9.02	-4.59	2.51	1.75	1.75	0.37
2019 Oct	500.00	4.00	Model	10.10	0.31	-9.24	0.00	18.63	0.00	-8.77	6.31	-7.59	8.92	-8.54	6.50	0.00	0.00	-2.70
2019 Oct	500.00	4.00	Operation	9.92	0.35	-14.90	0.04	12.98	0.17	-9.20	8.97	-10.38	10.20	-8.30	5.35	0.82	-0.07	-2.70
2019 Jun	500.00	4.00	Model	10.10	0.31	-9.24	0.00	18.63	0.00	-8.77	6.31	-7.59	8.92	-8.54	6.50	0.00	0.00	-2.70
2019 Jun	500.00	4.00	Operation	9.92	0.35	-14.64	-0.18	13.28	0.26	-9.20	-8.70	8.20	-9.90	9.94	-8.80	8.30	-9.70	9.60
2018 Jun	500.00	3.05	Model	7.59	5.75	12.26	0.00	-19.48	0.00	11.41	-7.91	1.24	-0.24	8.02	-8.87	0.00	0.00	1.46
2018 Jun	500.00	3.05	Operation	10.34	0.41	-10.76	0.00	-12.96	0.00	10.66	1.83	2.14	1.88	1.32	0.59	1.33	1.33	0.90
2016 Feb	390.00	2.90	Model	7.00	5.30	5.98	0.00	-20.00	0.00	8.97	-6.50	0.02	-0.53	8.47	-6.16	0.00	0.00	2.87
2016 Feb	390.00	2.90	Operation	7.00	5.30	-	-	-	-	-	-	-	-	-	-	-	-	-