The 50th ICFA Advanced Beam Dynamics Workshop on Energy Recovery Linacs

Envelope Matching from Injector to Main Linac for ERL

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KEK, High Energy Accelerator Research Organization
Tsukuba, Japan

T. Miyajima [A], M. Shimada [A], N. Nakamura [A], S. Sakanaka [A], K. Harada [A],
T. Obina [A], K. Kobayashi [A], R. Hajima [B] and Hwang Ji-Gwang [C]
[A] KEK, High Energy Accelerator Research Organization, Japan
[B] JAEA, Japan Atomic Energy Agency, Japan
[C] Kyungpook National University

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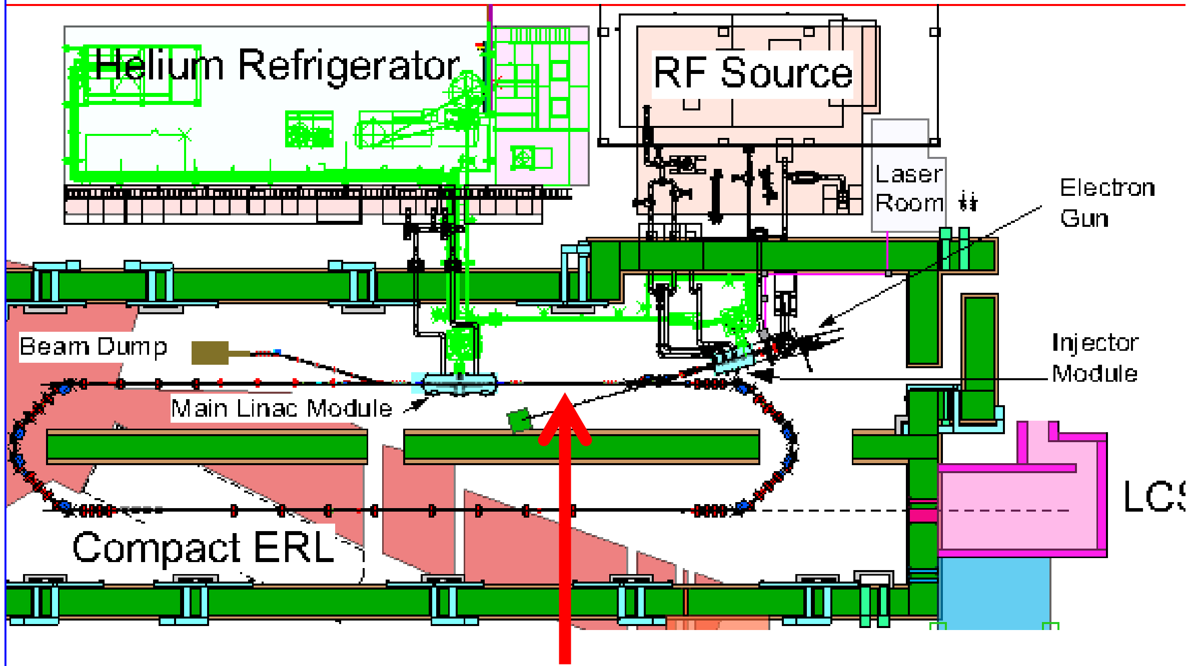
Optics Design for cERL 1st commissioning

- We are designing a beam optics for the compact ERL (cERL) 1st commissioning.
- The layout has a long straight section (8 m) from the exit of merger to the entrance of main linac for diagnostic system.
- In the future, main SRF cavities will be installed on the long straight section.

Parameters of the Compact ERL 1st commissioning

	Parameters
Gun voltage	500 kV
Injection energy	5 MeV
Beam energy	35 MeV
Average current	10 mA (7.7 PC/bunch)
Acc. gradient (injector)	7.5 MV/m
Acc. gradient (main linac)	15 MV/m
Normalized emittance	< 1 mm·mrad
Bunch length (rms)	1 - 3 ps (usual)
RF frequency	1.3 GHz

5 MeV beam paths through the long straight section.

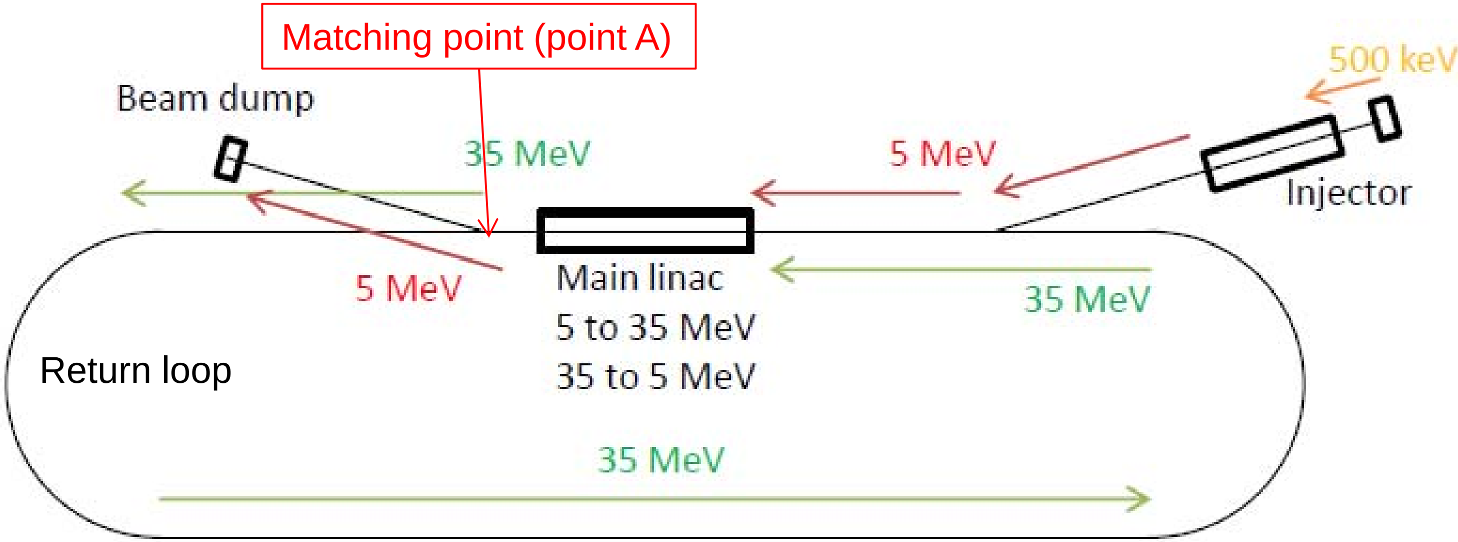


Long straight for additional SRF cavities in the future.
The straight section is used for beam instrumentation to measure injected beam.

Matching condition from injector to main linac

- To match the beam from an injector to a return loop, 6D particle distribution have to be adjusted.
- Especially, the envelope matching to adjust the Twiss parameter at a matching point is very important for the beam optics in the return loop.

- The matching point (point A) is the exit of main linac with 35 MeV beam energy.
- The beam optics from the gun to the matching point is calculated by General Particle Tracer (GPT) [1] with 3D mesh based space charge routine, because space charge effect is not negligible for 5 MeV electron beam.



[1] Pulsar Physics, http://www.pulsar.nl/gpt/index.html

Matching condition at matching point

- At the matching point, the accelerated beam have to satisfy the following matching condition.

1. Match Twiss parameters at the matching point

   $1 < \beta_x < 5$ m

   $6 < \beta_y < 18$ m

   $-0.3 < \alpha_x < -0.1$

   $2.5 < \alpha_y < 3.5$

   The optics in the return loop require these range of Twiss parameters at the matching point.

2. Control emittance and bunch length at the matching point

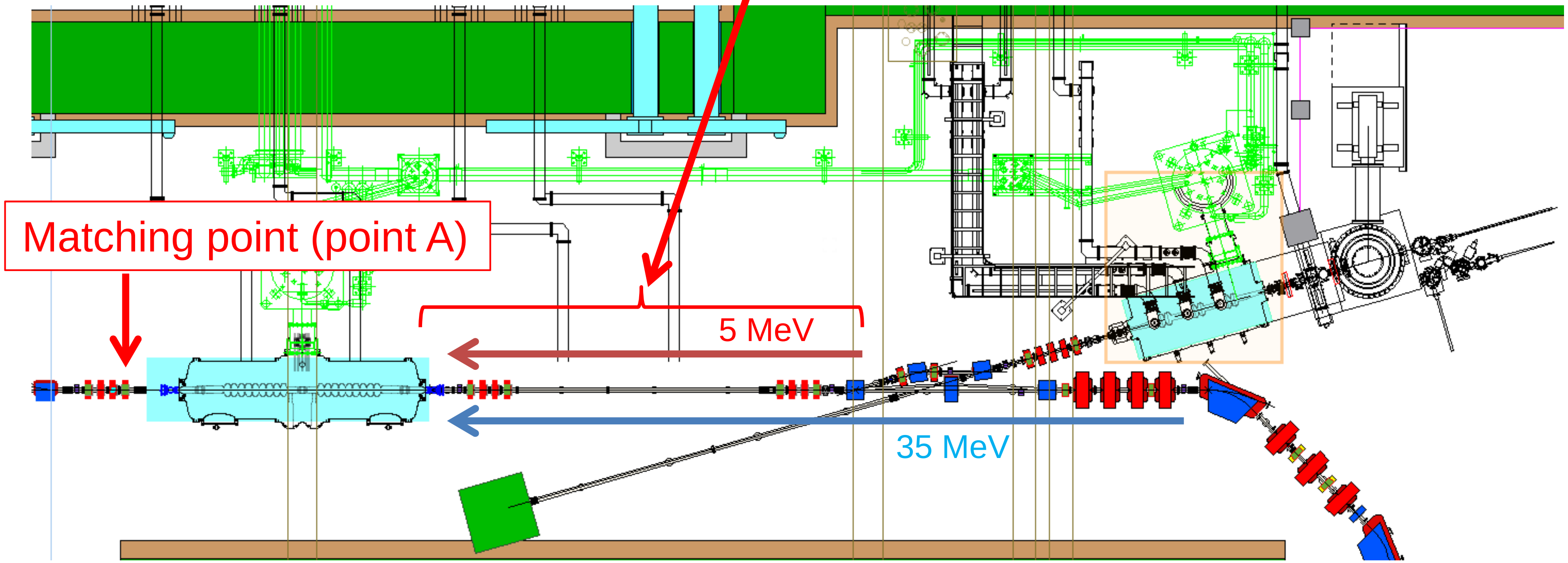
   Target emittance: < 1.0 mm mrad

   Bunch length: 1 to 3 ps (0.3 to 0.9 mm)

3. Control strengths of quadrupole magnets after the exit of merger

   5 MeV and 35 MeV beam path through the long straight section.

   Since the energy ratio of the injector and return loop is not larger, the strengths of the quadrupole magnets are limited to be less than 15 m^{-1} to reduce the effect on the decelerated beam.



How to match injector beam to main linac?

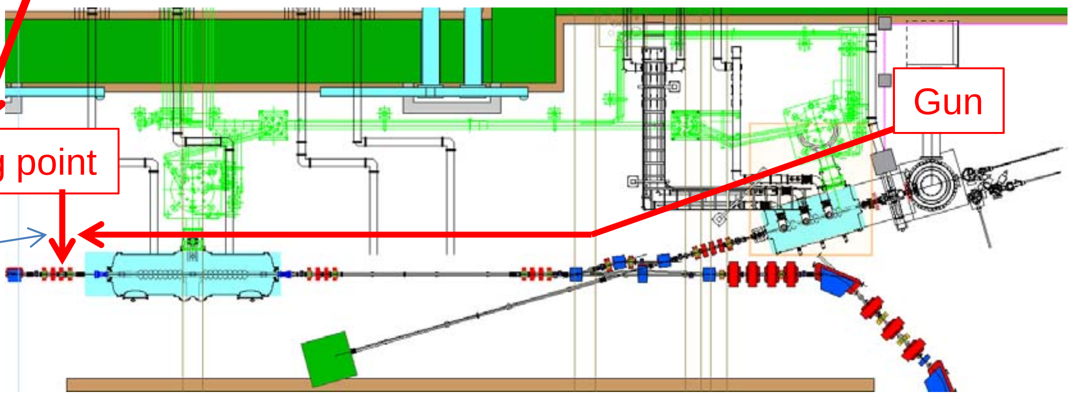
- The beamline parameters form the gun to the matching point were optimized using “multi objective method”[2].
- Tracking code: General Particle Tracer (GPT) with mesh based 3D space charge calculation
- Initial particle distribution at cathode: beer-can
- Initial laser pulse full width: 16 ps (fixed parameter)
- Single-step optimization: from cathode to the matching point (point A)
- Emittance and bunch length at the matching point are minimized.
- Twiss parameters at the matching point are restricted.

Optimized parameters: Total 23 parameters

- Laser diameter (1)
- Two solenoid strength (2)
- Voltage of buncher (1)
- Voltages of three injector cavities (3)
- Phase of three injector cavities (3)
- 5 quadrupole strengths before merger (5)
- 8 quadrupole strengths after merger (8)

Constraints of Twiss parameters at the matching point

$1 < \beta_x < 5$ m
$6 < \beta_y < 18$ m
$-0.3 < \alpha_x < -0.1$
$2.5 < \alpha_y < 3.5$

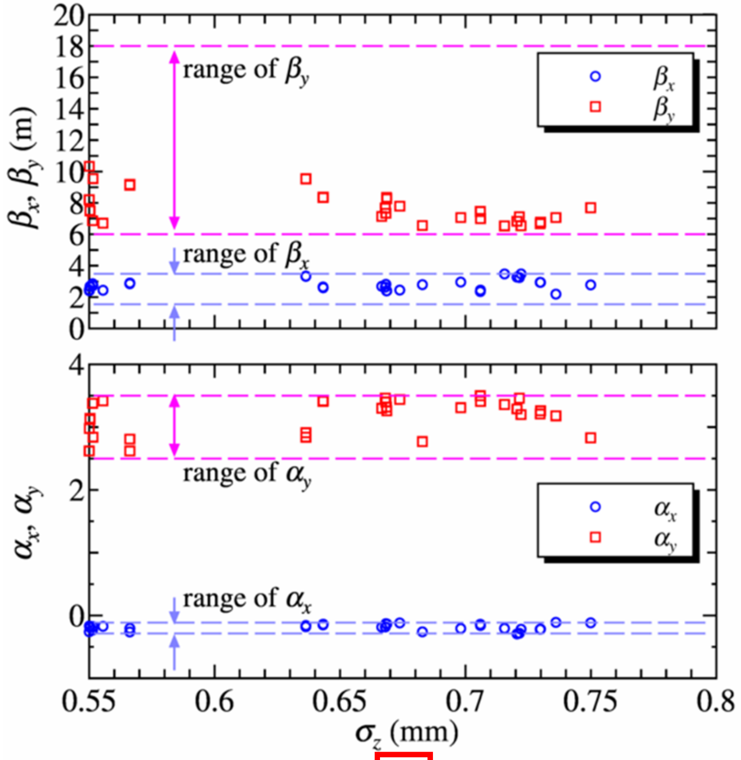


Minimize transverse emittance and bunch length with constraints of Twiss parameters

[2] Ivan V. Bazarov and Charles K. Sinclair , Phys. Rev. ST Accel. Beams 8, 034202 (2005).

Results of single-step optimization

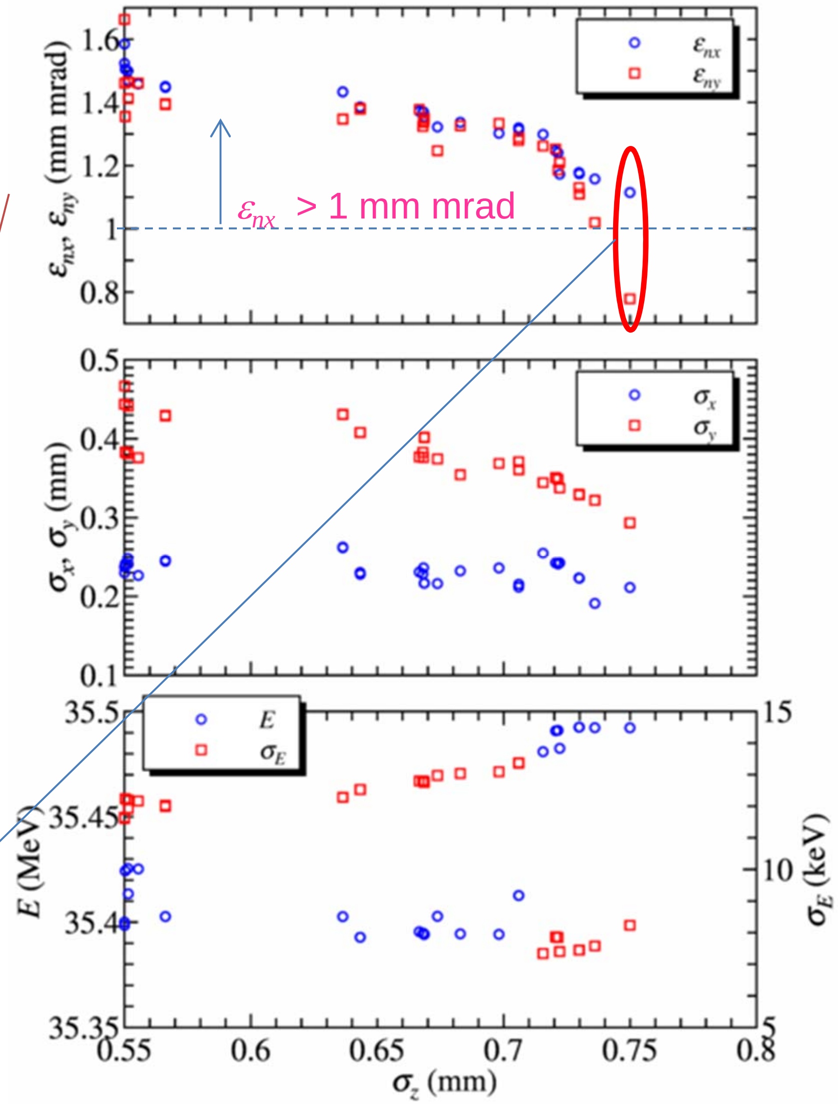
- Twiss parameters at the matching point



Twiss parameters satisfy the matching condition. However, minimum emittance is not smaller than 1.0 mm mrad.

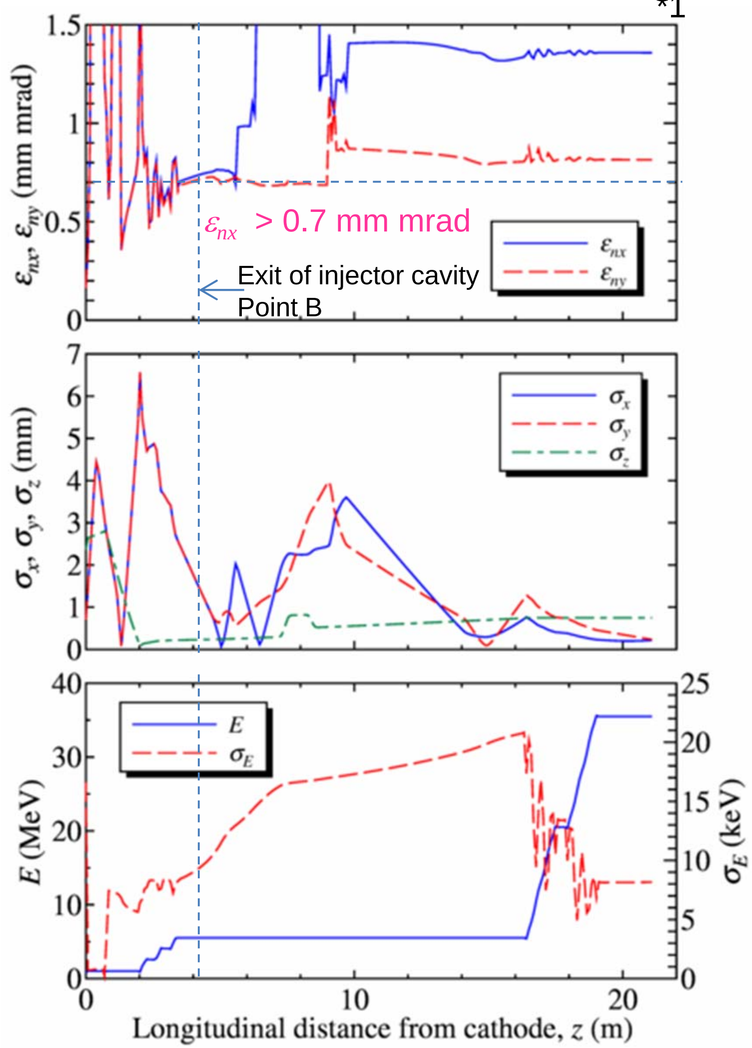
Time evolution of the emittance for an optimized parameter set was calculated as shown in next slide.

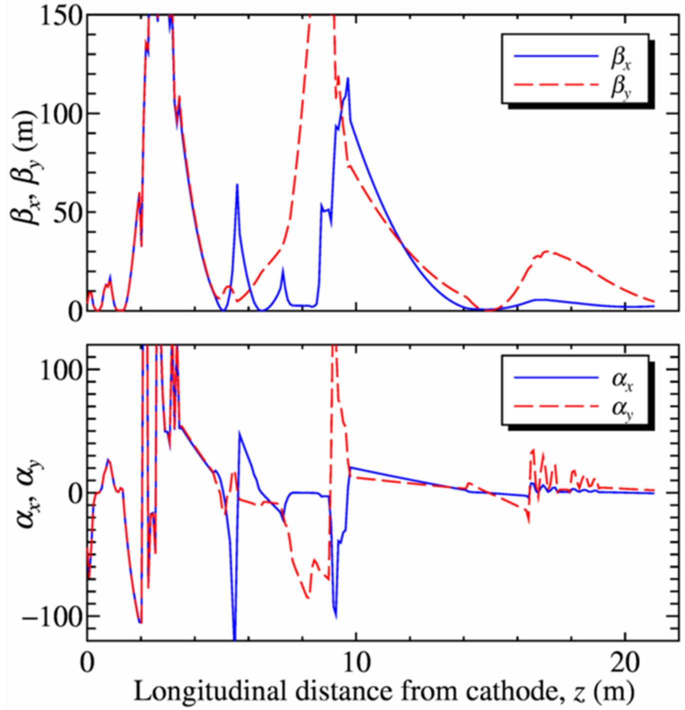
- Emittance and beam size at the matching point



Time evolutions of beam parameters

- The time evolution of the beam parameters with the optimized beamline parameters by the single-step optimization.





After the injector cavity, the emittance exceeds 0.7 mm mrad.
For 7.7 pC/bunch, we may obtain smaller emittance, for example 0.2 mm mrad.
What does limit the emittance?

*1 The horizontal emittance in the time evolution calculation is 1.3 mm mrad. It is larger than the emittance in the optimization, 1.1 mm mrad. The different output commands in GPT, 'tout' for time evolution, 'screen' for optimization, caused it.

What dose limit emittance?

- In order to investigate the origin of the emittance growth, we used the following two methods.

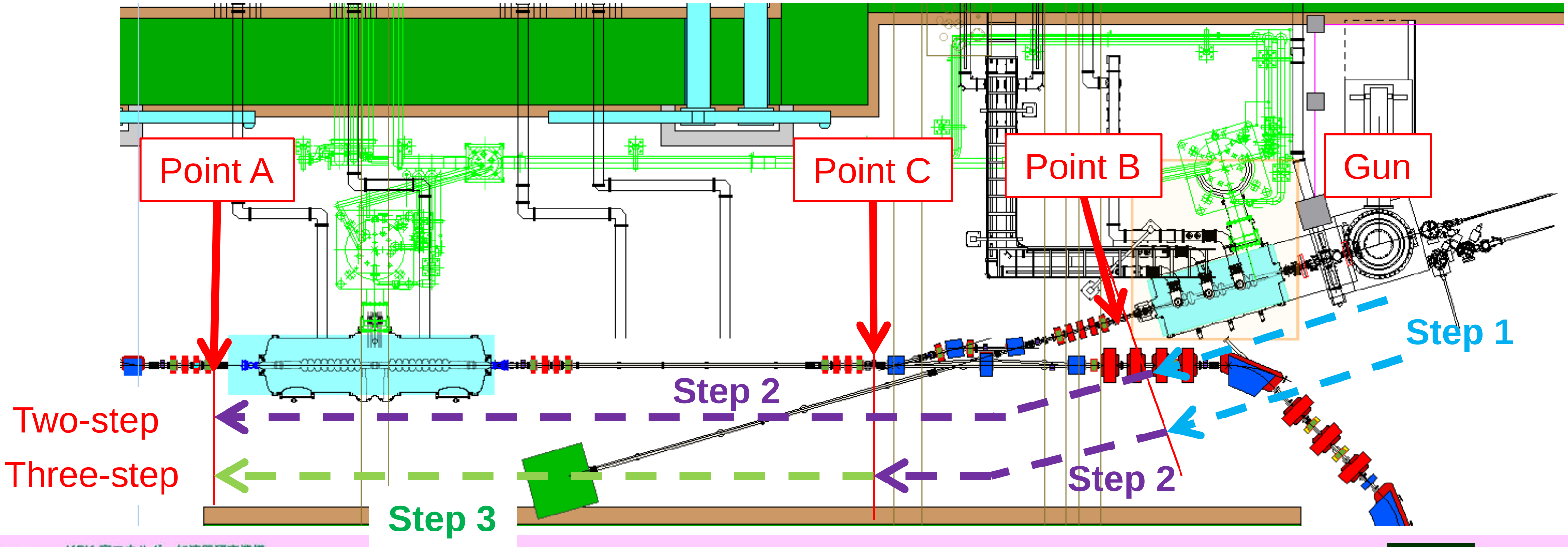
<u>(1) Two-step optimization</u>

  - Step 1. Minimize emittance and bunch length at the exit of the injector cavity (point B),
  - Step 2. Minimize emittance at the matching point (point A) from point B.

- At point B, we can estimate the minimum emittance in the injector.

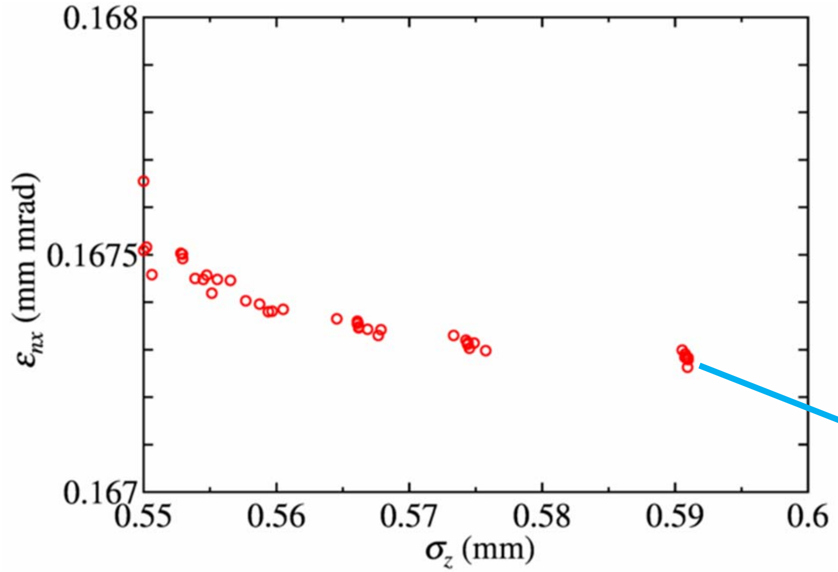
<u>(2) Three-step optimization</u>

- The beamline is divided into three parts.
  - Step 1. Minimize emittance and bunch length at point B (same as Two-step optimization)
  - 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)

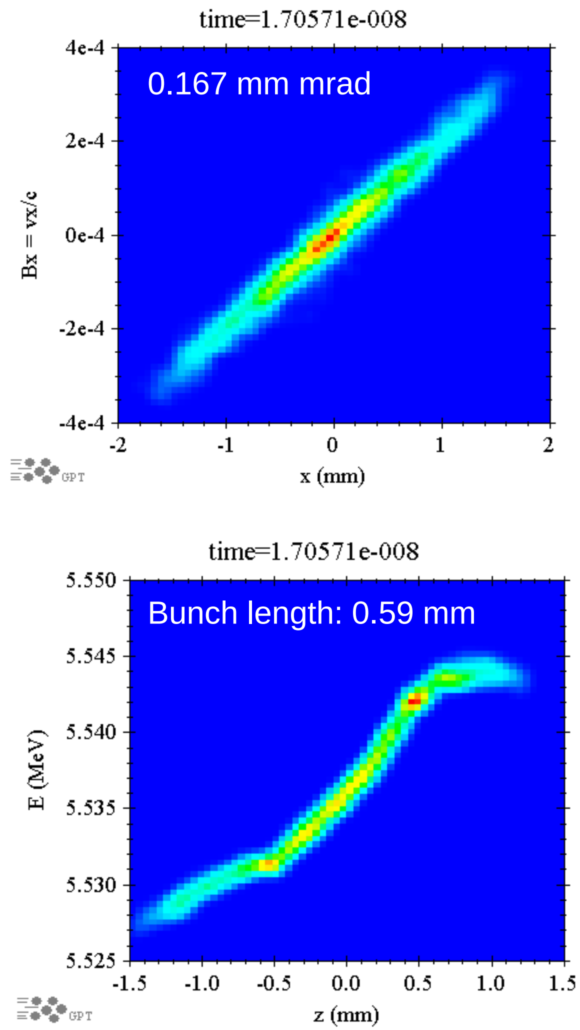


Results of step-1 in two-step optimization at point B

- Emittance and bunch length at the exit of injector cavity(point B).



Particle distribution at point B



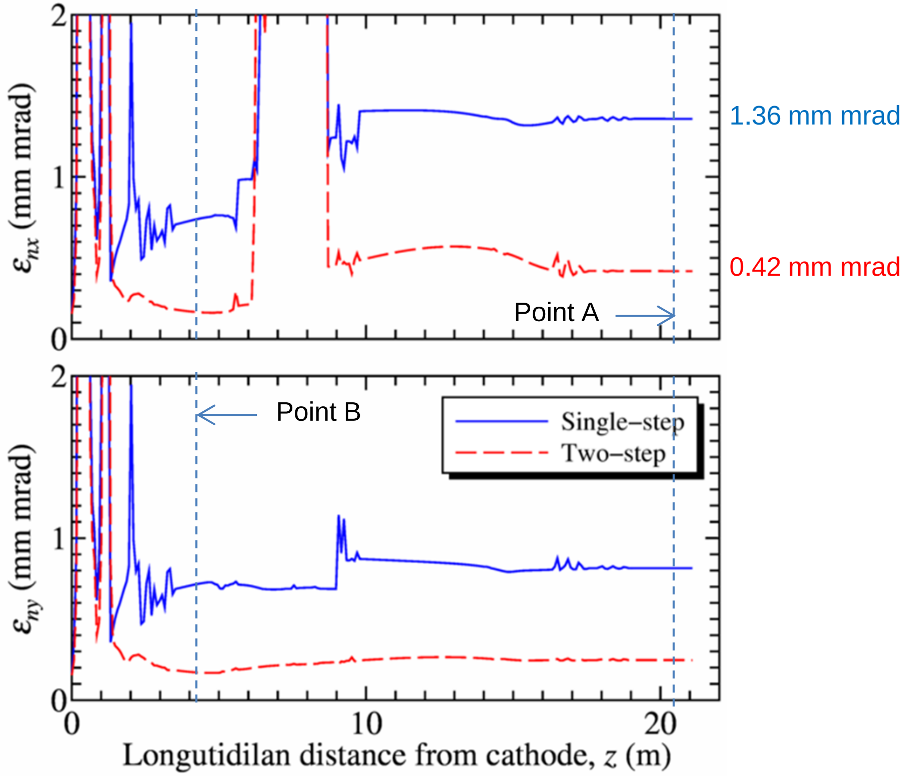
Minimum emittance: 0.167 mm mrad with bunch length of 0.59 mm
Therefore, the minimum emittance in the injector is less than 0.2 mm.

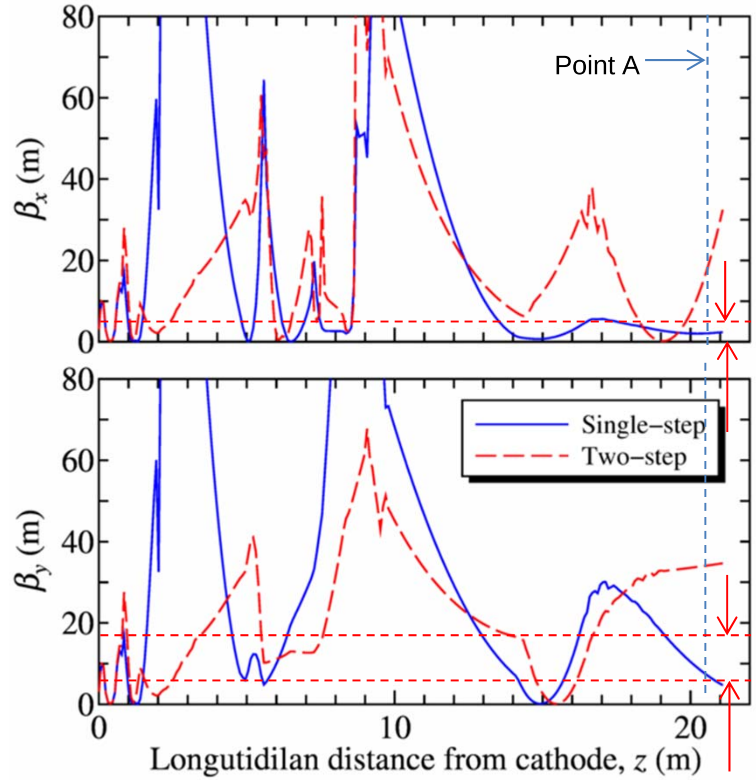
Using the optimized beamline parameter set, the particle distribution at point B was calculated.

In the second step,
5 quadrupole magnets before the merger and 8 quadrupole magnets are optimized to minimize emittance at the matching point (point A) and to adjust beam envelope.

Results of step-2, Emittance growth after injector cavities

- 5 quadrupoles before merger and 8 quadrupole after merger were optimized from the point B using the particle distribution at the point B.





<u>Minimum emittance</u>

Single-step optimization: 1.36 mm mrad (h)

Two-step optimization: 0.42 mm mrad (h)

Two-step optimization gives smaller emittance at the matching point (point A).

However, Twiss parameters optimized by Two-step optimization don't satisfy the matching condition at point A.

The results shows that the matching condition limit the emittance.

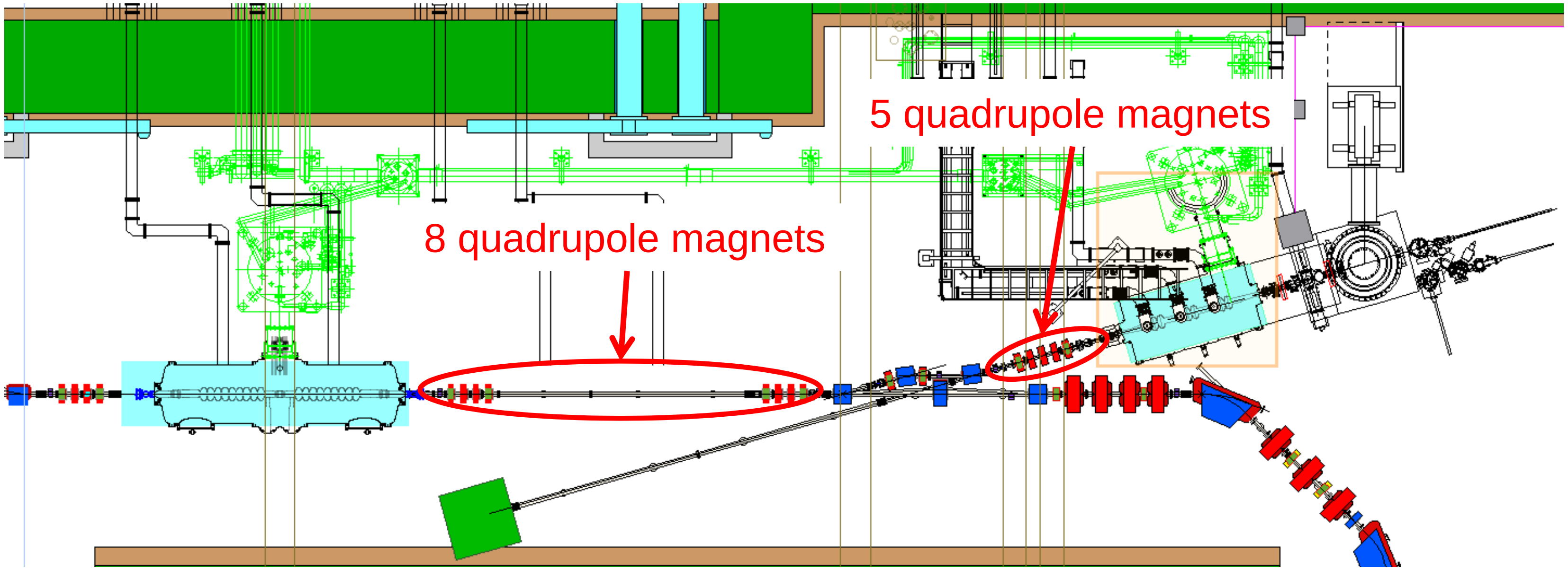
Purpose of quadrupole magnets

- <u>5 quadrupole magnets before merger</u>:
  - To match the envelope at the exit of merger to minimize emittance growth caused by LSC and dispersion in merger section [3].
- <u>8 quadrupole magnets after merger</u>:
  - To adjust the envelope at the matching point
  - To minimize emittance growth in the long straight section

[3] R. Hajima, Proc. of 1st Annual Meeting of Particle Accelerator Society of Japan and the 29th Linear Accelerator Meeting in Japan (August 4-6, 2004, Funabashi, Japan), 432 (2004).

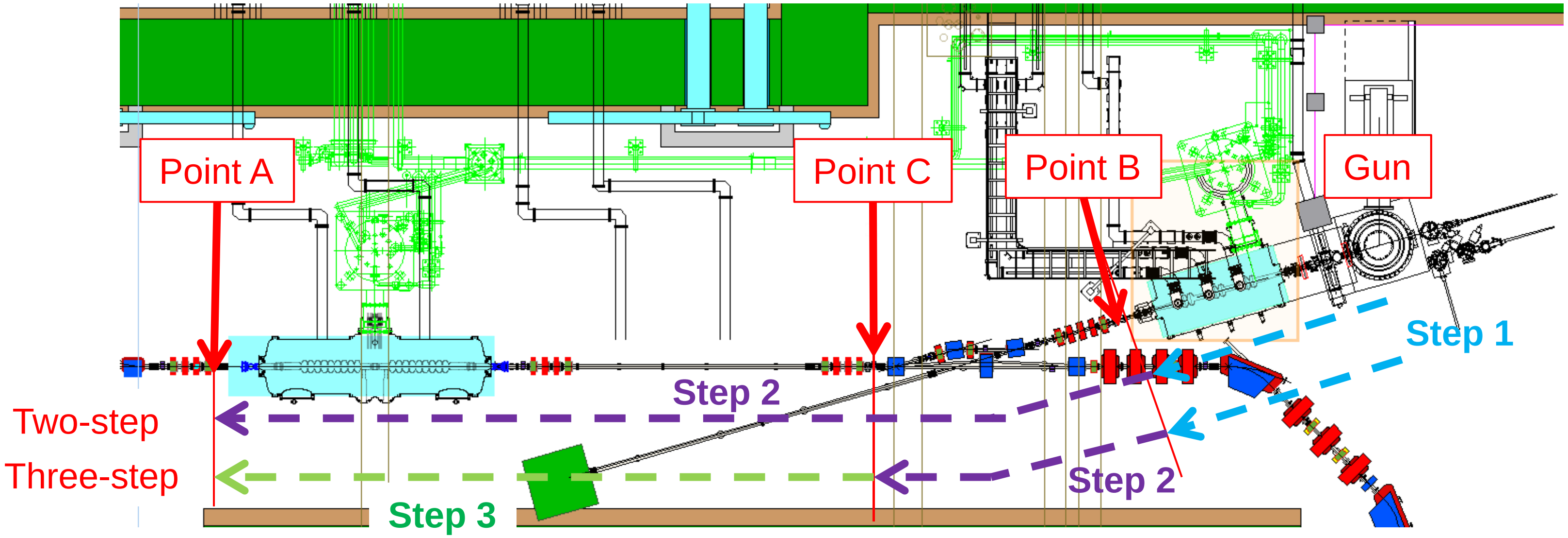
Does the envelope matching conflict with emittance minimization?
How large is the emittance growth in the long straight section?

⇨ Three-step optimization



Three-step optimization

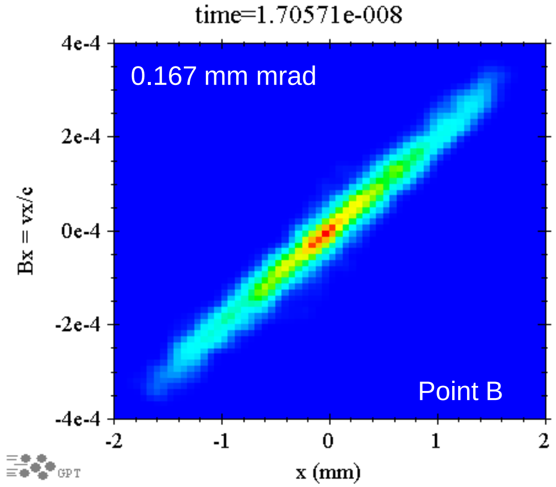
- Step 1. Minimize emittance and bunch length at point B (same as Two-step optimization)
- Step 2. Minimize emittance at the exit of the merger (point C), to estimate emittance growth in the merger
- Step 3. Minimize emittance at point A, (emittance compensation and envelope matching)

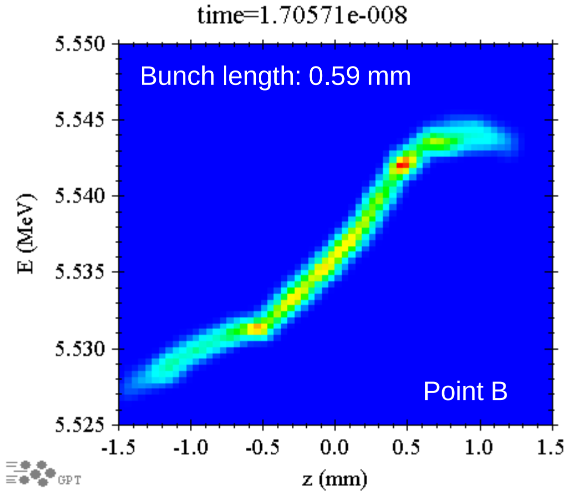


Results of step-2: particle distribution at point C

- In the second step, the 5 quadrupoles magnets is adjusted to minimize emittance growth between point B to point C.
- Initial particle distribution at point B: same as Two-step optimization

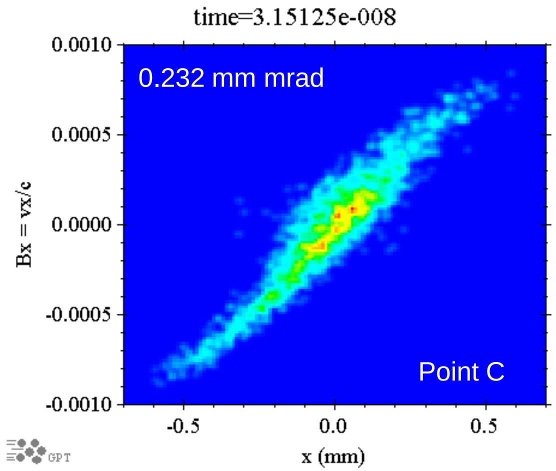
<u>Particle distribution at point B</u>
Emittance: 0.167 mm mrad
Bunch length: 0.59 mm

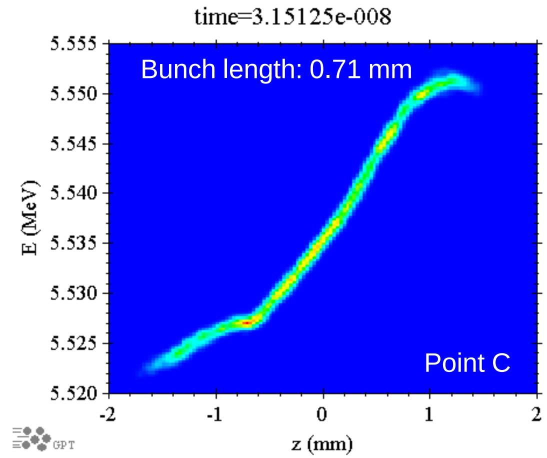




Point B to point C through merger

<u>Particle distribution at point C</u>
Emittance: 0.232 mm mrad
Bunch length: 0.71 mm

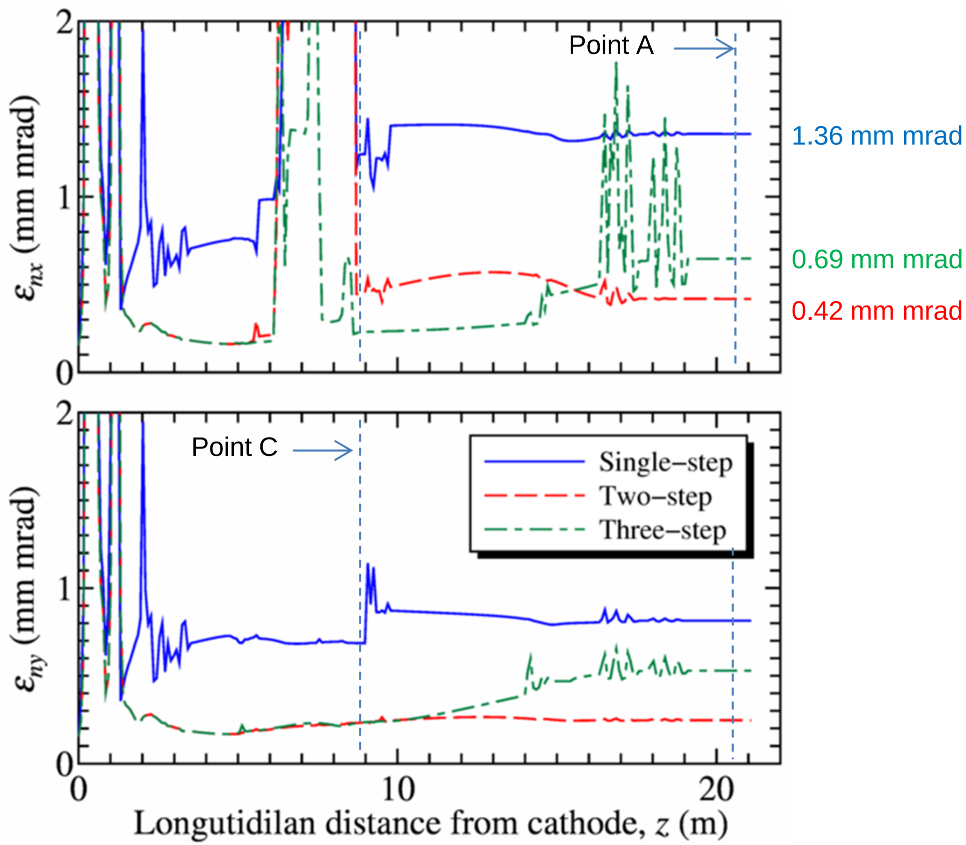


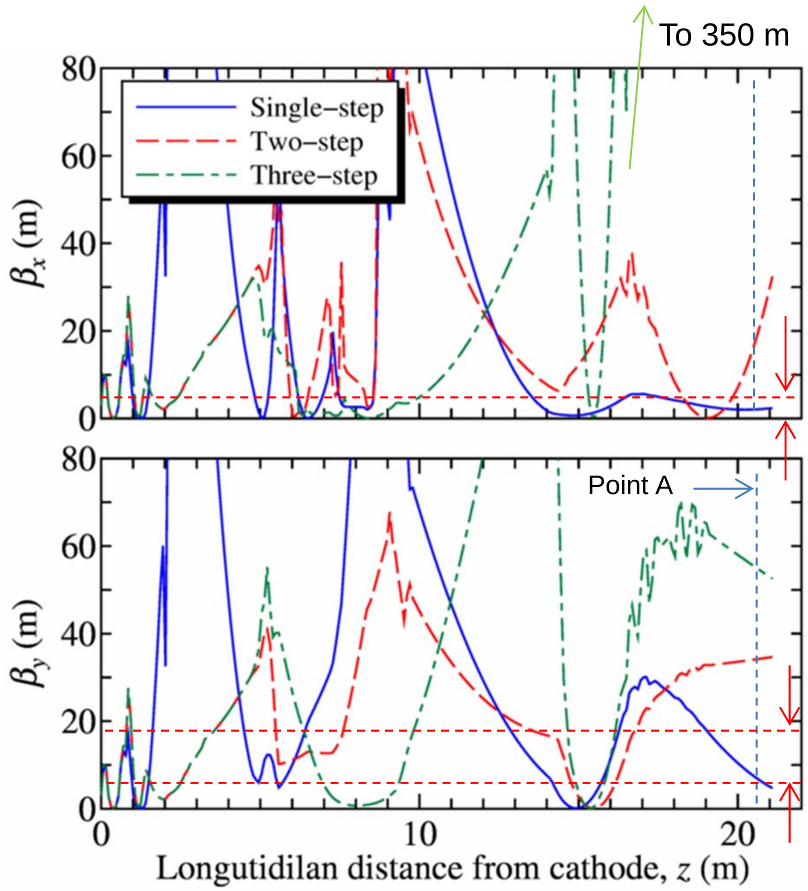


In this case, the emittance growth in the merger is 0.065 mm mrad.
In the third step, 8 quadrupole magnets were optimized as shown in next slide.

Results of step-3 (at point A)

- Optimization results from point C to point A



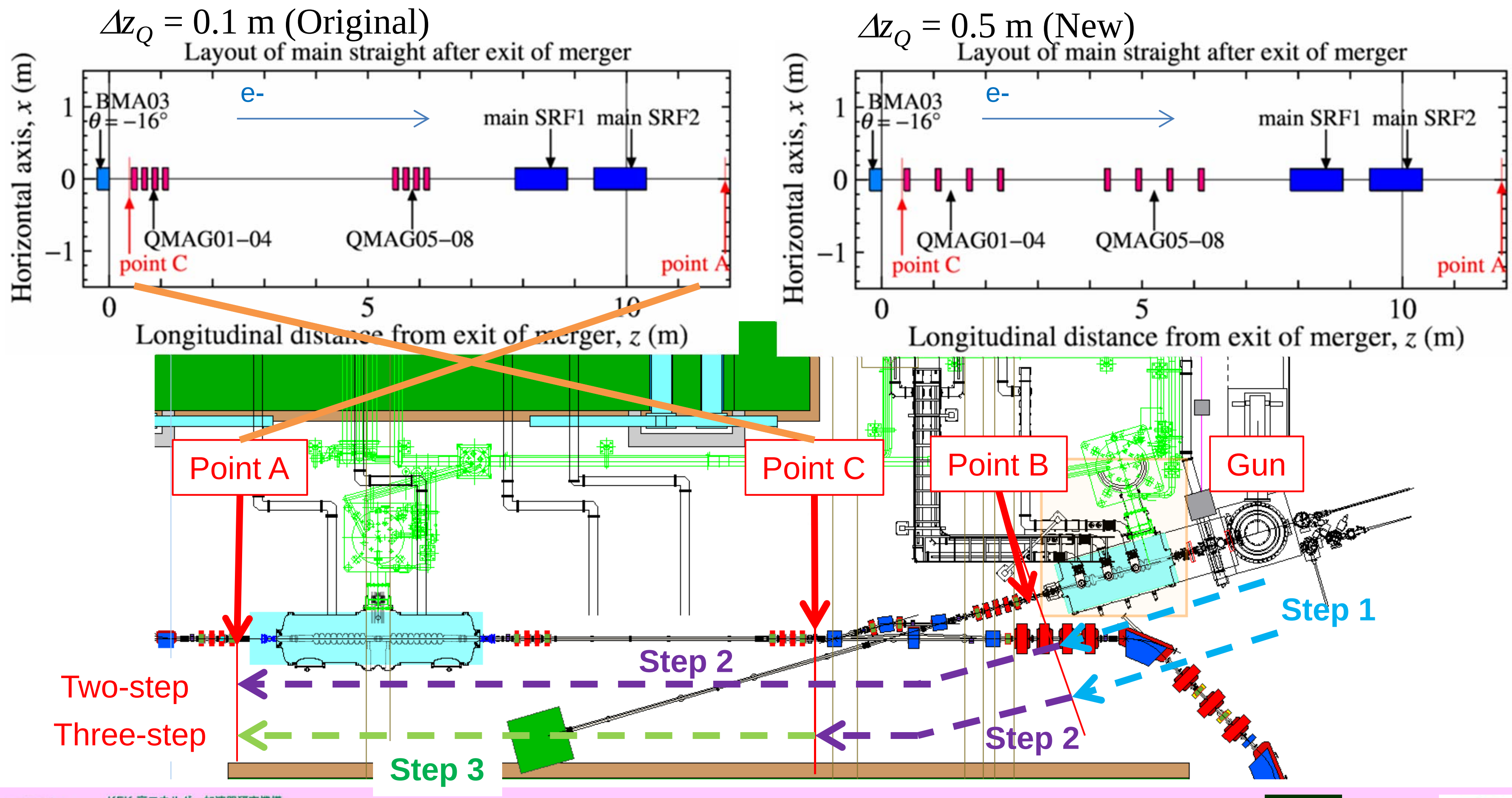


At point C, three-step optimization gives 0.232 mm mrad. It gives minimum emittance at the point C.
However, final emittance at point A increased to be 0.691 mm mrad.

Betatron functions for three-step optimization become too larger, and dose not satisfy the matching condition.
In this case, we fond a conflict between the minimization of emittance and the envelope matching.
Is the layout of the long straight relevant?

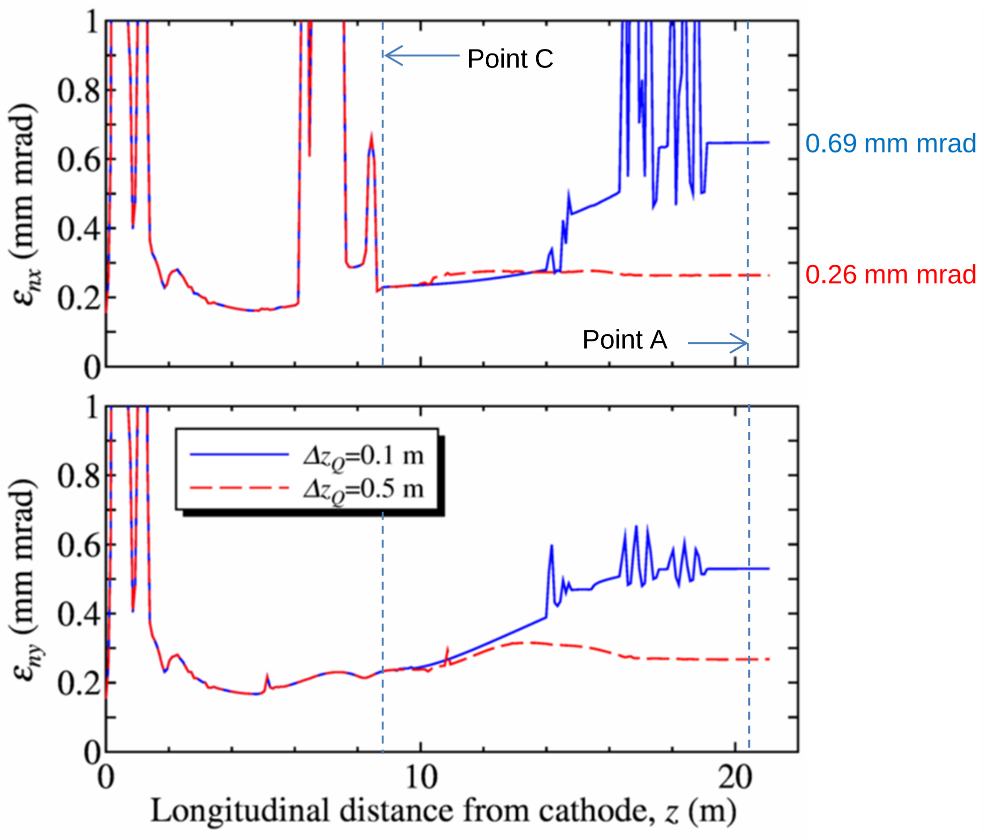
Layout of quadrupole magnets in long straight

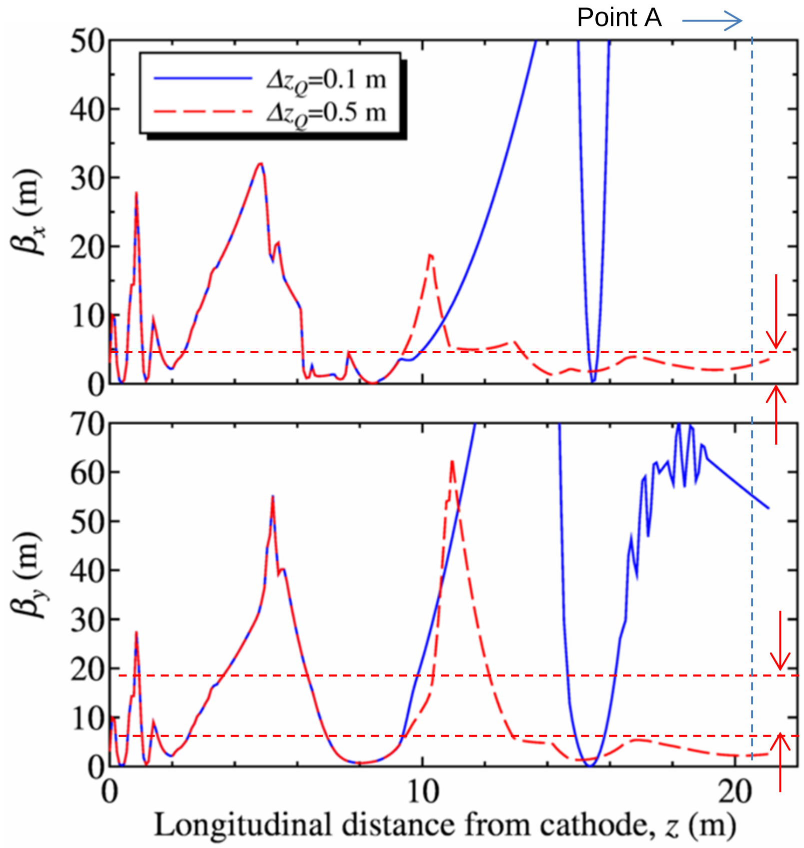
- In order to investigate effect of long straight layout, the two layouts of the quadrupole magnets were used.
  - Original layout: distance between quadrupoles is 0.1 m.
  - New layout: distance between quadrupole is 0.5 m.



Results for different layouts in long straight

- Optimized results from point C to point A





Original layout(Δz_Q=0.1 m): 0.691 mm mrad
New layout(Δz_Q=0.5 m): 0.262 mm mrad
The new layout with Δz_Q=0.5 m gives small emittance at point C.

The new layout (Δz_Q=0.5 m) did not satisfy the matching condition at point A. However, betatron function remained to be less than 10 m.

Therefore, using relevant long straight layout we can achieve small emittance and small betatron function.

Summary

- We are designing a beam optics for the compact ERL (cERL) 1st commissioning with injection energy of 5 MeV, main linac energy of 35 MeV and 7.7 pC/bunch.
- The layout has a long straight section (8 m) from the exit of merger to the entrance of main linac for diagnostic system.
- At a matching point (exit of the main linac), the accelerated beam have to satisfy the following matching conditions,
  - Constraints of Twiss parameters
  - Minimization of Emittance and bunch length
  - Control the strengths of quadrupole magnets after the exit of merger
- We optimized the beamline parameters from the gun to the matching point using three optimizations.
  - Single-step: 1.36 mm mrad, it satisfies the matching condition of Twiss parameters.
  - Two-step: 0.42 mm mrad, it dose not satisfy the matching condition.
  - Three-step: 0.26 mm mrad with appropriate layout of long straight, it dose not satisfy the matching condition. However, betatron function after merger is less than 10 m.
- We found a conflict between the minimization of emittance and the envelope matching in the long straight section.
- Using relevant long straight layout, we can achieve small emittance and small betatron function.
- In the future, we will try to optics tuning in the return loop to connect the results of three-step optimization.

Back-up slide

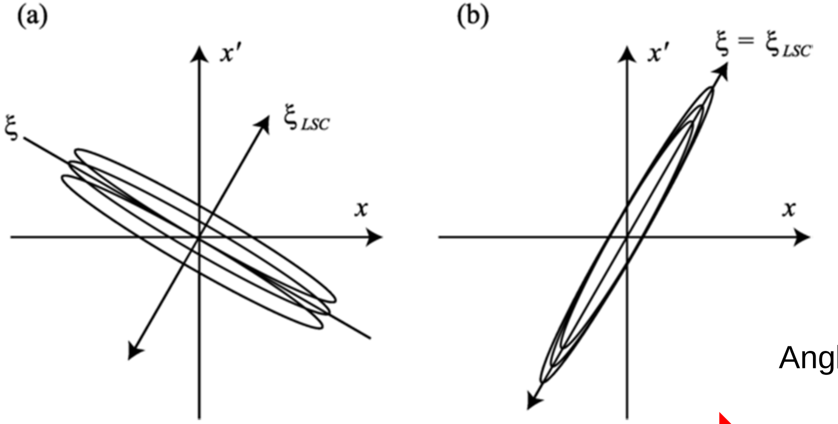
ERL collaboration team

- High Energy Accelerator Research Organization (KEK)
  - M. Akemoto, T. Aoto, D. Arakawa, S. Asaoka, A. Enomoto, S. Fukuda, K. Furukawa, T. Furuya, K. Haga, K. Hara, K. Harada, T. Honda, Y. Honda, T. Honma, T. Honma, K. Hosoyama, M. Isawa, E. Kako, T. Kasuga, H. Katagiri, H. Kawata, Y. Kobayashi, Y. Kojima, T. Matsumoto, H. Matsushita, S. Michizono, T. Mitsuhashi, T. Miura, T. Miyajima, H. Miyauchi, S. Nagahashi, H. Nakai, H. Nakajima, E. Nakamura, K. Nakanishi, K. Nakao, T. Nogami, S. Noguchi, S. Nozawa, T. Obina, S. Ohsawa, T. Ozaki, C. Pak, H. Sakai, S. Sakanaka, H. Sasaki, Y. Sato, K. Satoh, M. Satoh, T. Shidara, M. Shimada, T. Shioya, T. Shishido, T. Suwada, T. Takahashi, R. Takai, T. Takenaka, Y. Tanimoto, M. Tobiyama, K. Tsuchiya, T. Uchiyama, A. Ueda, K. Umemori, K. Watanabe, M. Yamamoto, Y. Yamamoto, S. Yamamoto, Y. Yano, M. Yoshida
- Japan Atomic Energy Agency (JAEA)
  - R. Hajima, R. Nagai, N. Nishimori, M. Sawamura
- Institute for Solid State Physics (ISSP), University of Tokyo
  - N. Nakamura, I Itoh, H. Kudoh, T. Shibuya, K. Shinoe, H. Takaki
- UVSOR, Institute for Molecular Science
  - M. Katoh, M. Adachi
- Hiroshima University
  - M. Kuriki, H. Iijima, S. Matsuba
- Nagoya University
  - Y. Takeda, T. Nakanishi, M. Kuwahara, T. Ujihara, M. Okumi
- National Institute of Advanced Industrial Science and Technology (AIST)
  - D. Yoshitomi, K. Torizuka
- JASRI/SPring-8
  - H. Hanaki

Origin of emittance growth after injector cavity

- After the injector cavity, there are two important section to avoid emittance growth.
  - One is the merger section.
  - Other one is the long straight section.

<u>(1) Emittance growth in merger</u>



Energy change caused by Longitudinal space charge (LSC) force and dispersion function cause the emittance growth [3].

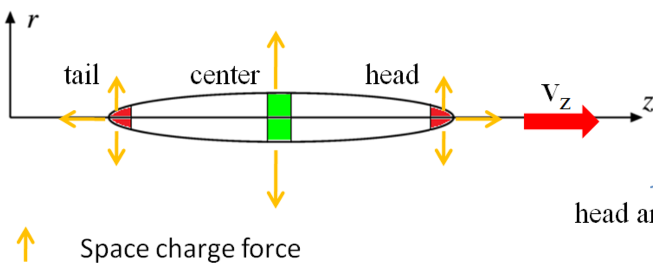
(a) Maximum emittance growth
(b) Minimum emittance growth

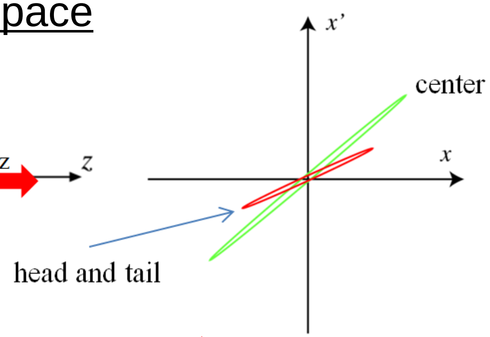
To reduce emittance growth at the exit of the merger, the Twiss parameters have to be adjusted like (b).

Angle of phase space distribution: $\xi = \frac{1}{2}\arctan\left(\sqrt{\frac{2\alpha_x}{\gamma_x - \beta_x}}\right)$

⇨ Adjust 5 quadrupole magnets before merger

<u>(2) Emittance growth in drift space</u>





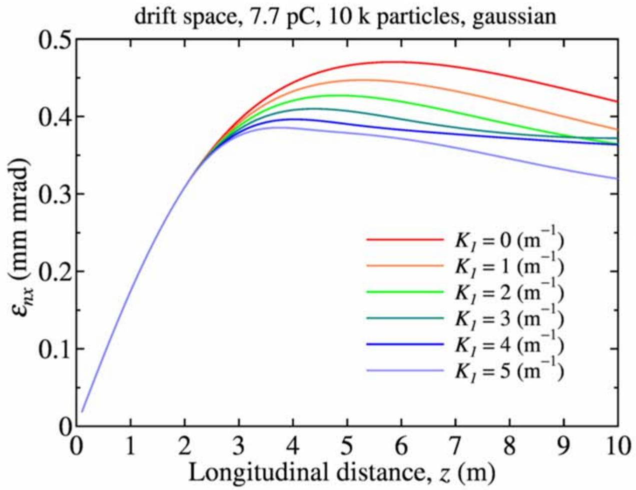
If the longitudinal charge density is not uniform, the transverse space charge force depends on the longitudinal position. And the difference of the transverse SC force causes the discrepancy of the slice in the phase space.

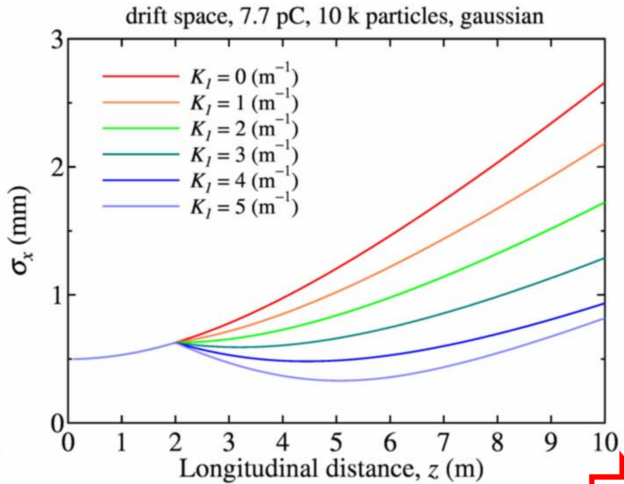
⇨ Adjust 8 quadrupole magnets after merger

[3] R. Hajima, Proc. of 1st Annual Meeting of Particle Accelerator Society of Japan and the 29th Linear Accelerator Meeting in Japan (August 4-6, 2004, Funabashi, Japan), 432 (2004).

Emittance growth in drift space with 5 MeV

- The emittance growth in a drift space with 5 MeV and 7.7 pC/bunch was calculated.
- A quadrupole magnet is placed at 2 m. The strength is varied from 0 to 5 m^{-1}.



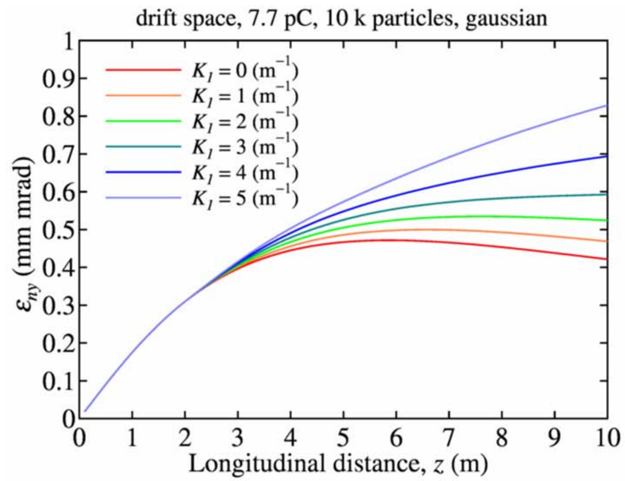


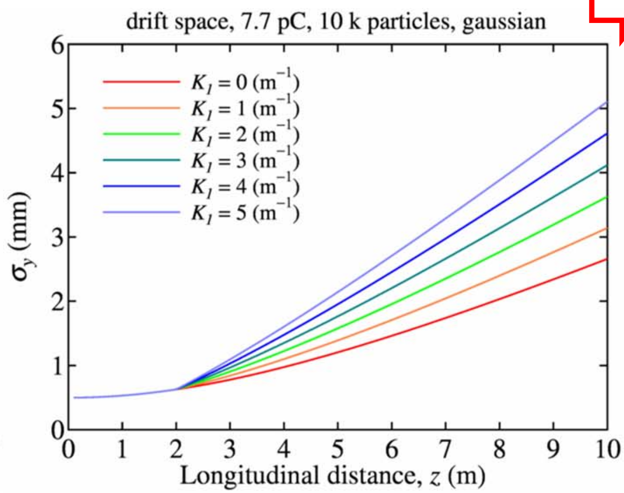
<u>Horizontal direction</u>

We can reduce the emittance growth in the drift space due to adjust quadrupole magnet strength.

The results shows that the appropriate layout of the quadrupole magnet can reduce the emittance growth.

In three-step optimization, we used other different layout of quadrupole magnets.

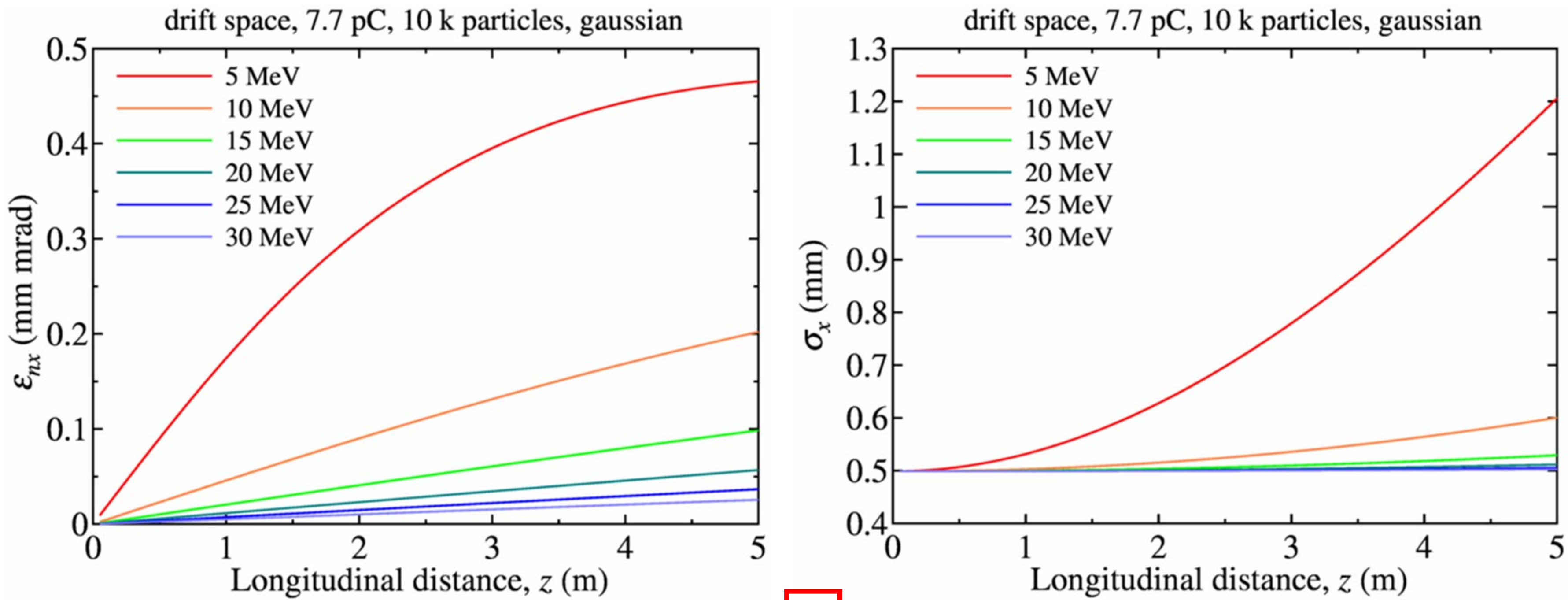




<u>Vertical direction</u>

Emittance growth in drift space

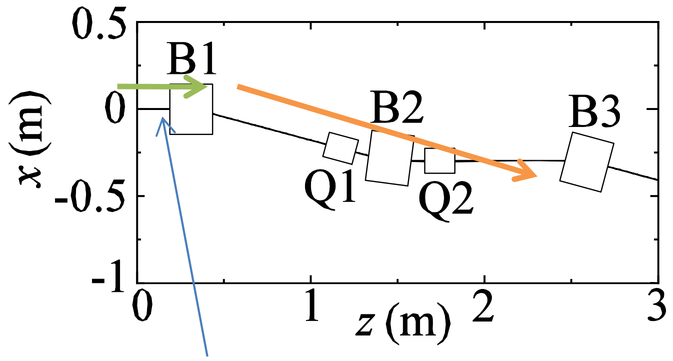
- Emittance growth in drift space with 7.7 pC/bunch.



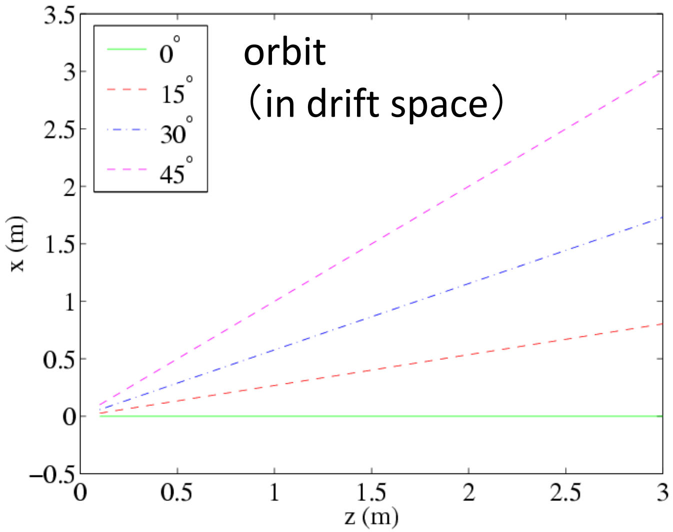
The results shows that the emittance growth with 5 MeV is not negligible.

Problem of space charge calculation in merger

- Merger section
- Original routine (spacecharge3dmesh)
  ⇒ calculated emittance is not correct.
- It is clear for smaller number of particles.
- We checked the source code.

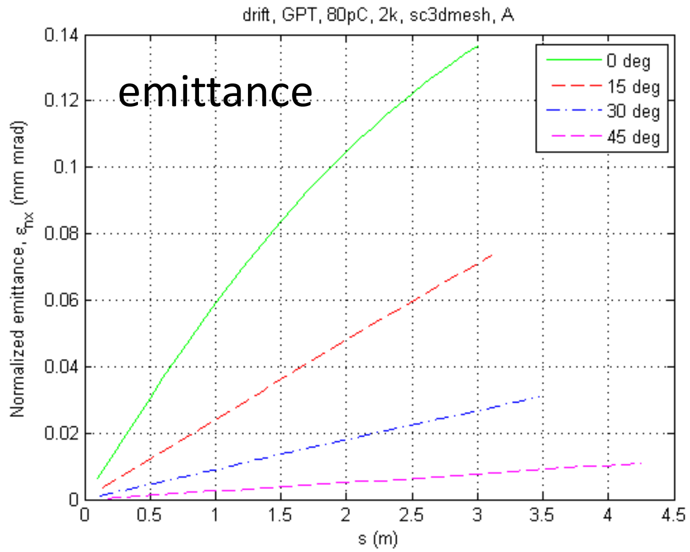


Beam goes forward along the following orbit.



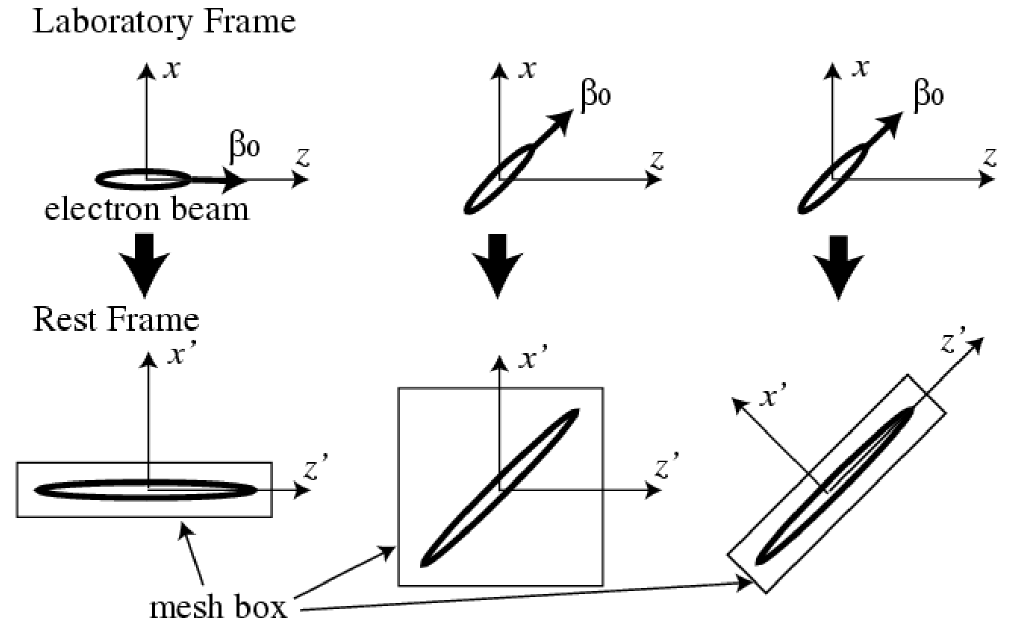
Calculated emittance depends on angle from z-axis.

Why?



Enhanced space charge calculation in GPT

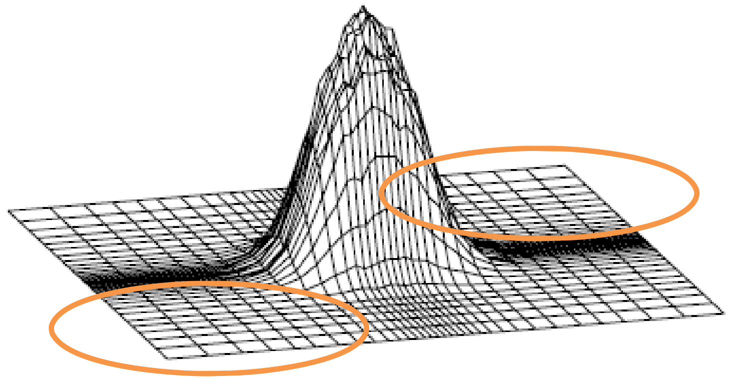
- In original spacecharge3dmesh routine,
  direction of mesh box : fixed to coordinate in GPT
- When beam go forward along oblique line fro z-axis,
  mesh size becomes coarse.



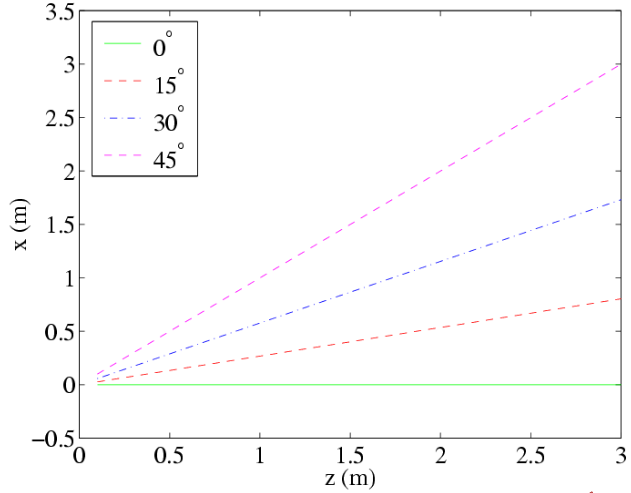
(a) Original routine along z-axis.

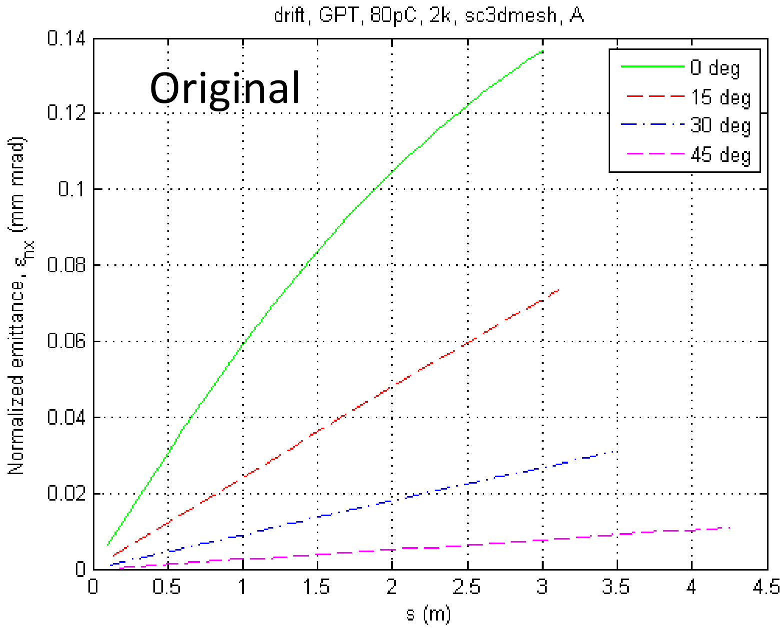
(b) Original routine 45 degree direction from z-axis.

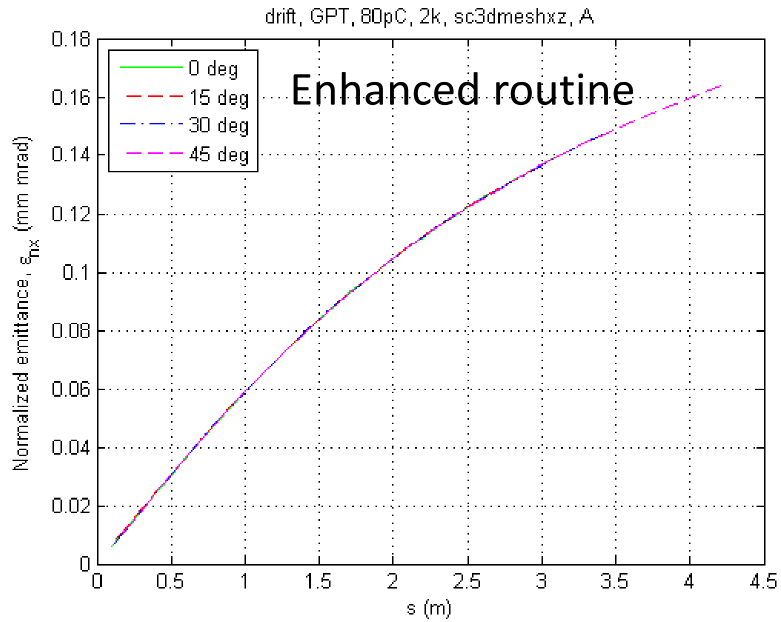
(c) New routine 45 degree direction from z-axis.



We made enhanced routine
⇒ spacecharge3dmeshxz





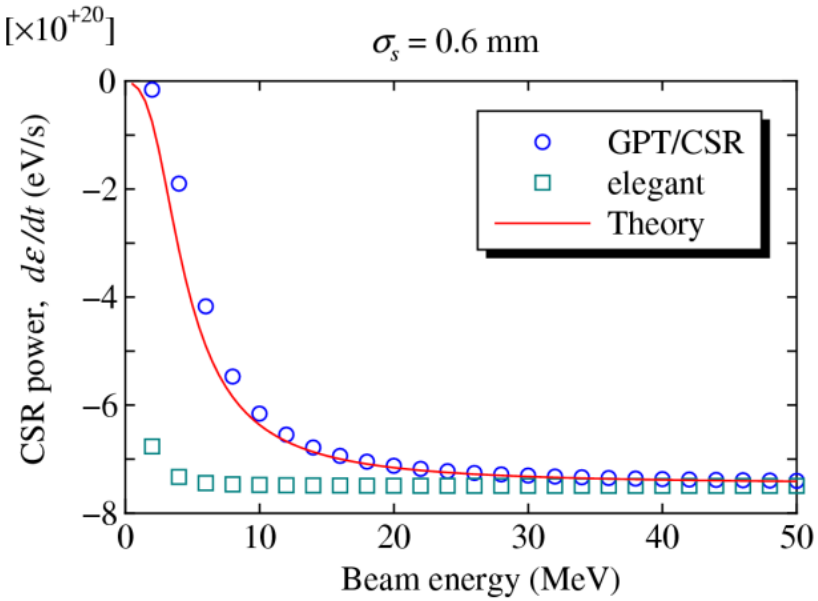


Spacecharge3dmeshxz
The enhanced routine can calculate the accurate emittance.

1D CSR routine in GPT

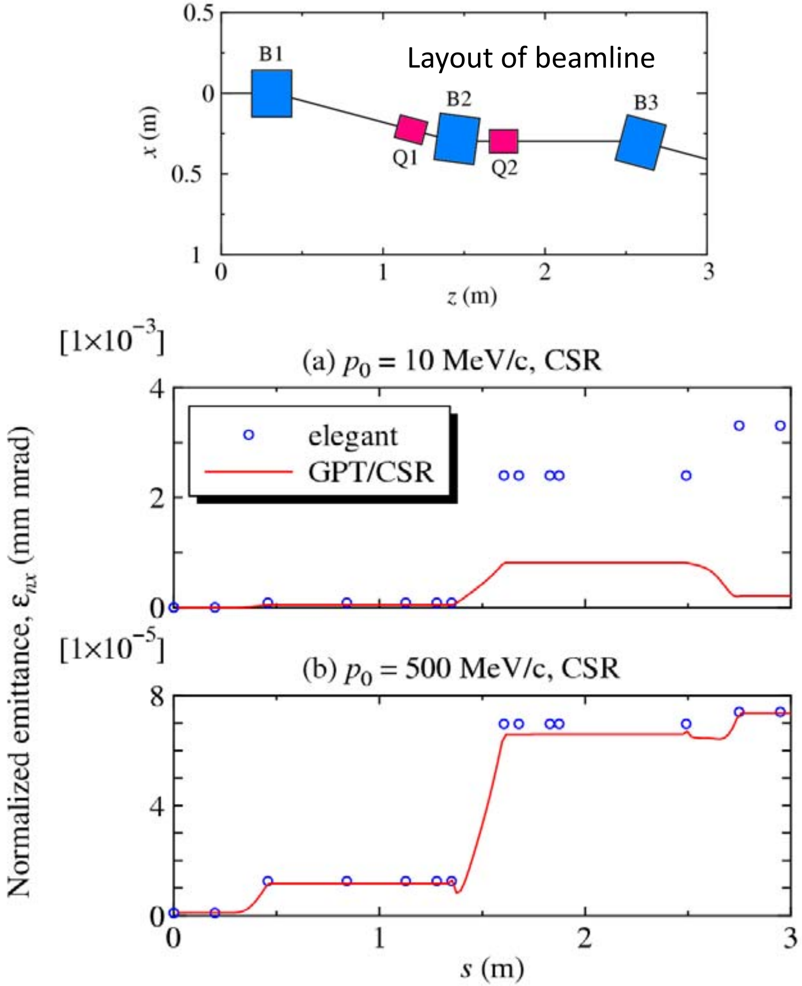
- We developed 1D CSR routine, which is effective in lower energy beam, e.g. beam energy of 10 MeV.
- Based on Sagan's formula[4]

(1) Energy loss due to CSR



<u>Using the CSR routine, we can calculate CSR effect in lower energy region, e.g. beam enegy of 10 MeV.</u>

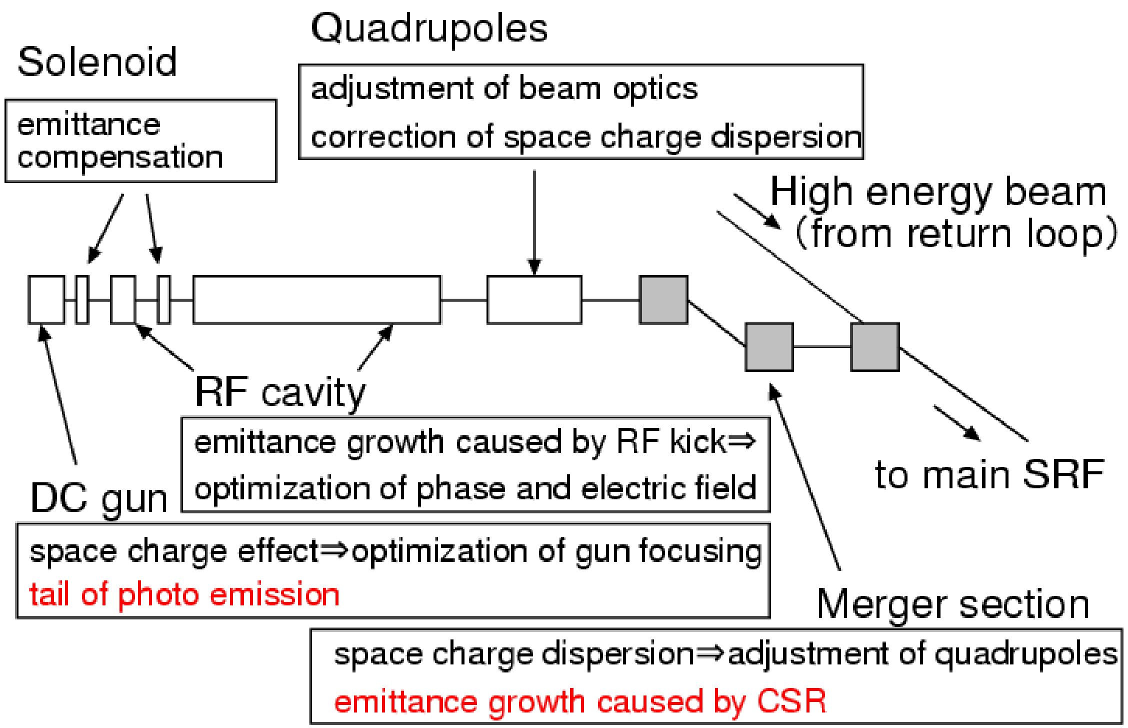
(2) Emittance growth caused by CSR



Physics in ERL injector

(1) Space charge effect（Coulomb force between electrons)
(2) Solenoid focusing（Emittance compensetion）
(3) RF kick in RF cavity
(4) Higher order dispersion in merger section
(5) Coherent Synchrotron Radiation (CSR) in merger section
(6) Response time of photo cathode（It generates tail of emission.）

These effects combine in the ERL injector.



To obtain high quality beam at the exit of merger, optimization of beamline parameters is required.

Method to research the beam dynamics:
Macro particle tracking simulation with space charge effect is used.

The simulation code have to include
(1) External electric and magnetic field,
(2) Space charge effect (3D space charge).

Effect of gun voltage

Preliminary results
Bunch charge: 20 pC/bunch
Gun voltage: 500 kV or 600 kV
At exit of merger

(1) 0.6 mm (2 ps) bunch length
enx = 0.14 mm mrad with 500 kV
enx = 0.13 mm mrad with 600 kV

(2) 0.9 mm (3 ps) bunch length
enx = 0.12 mm mrad with 500 kV
enx = 0.11 mm mrad with 600 kV

Results of Gun and solenoid beamline