Beam dynamics and optics issues

Shogo Sakanaka, KEK

for the ERL beam dynamics working group

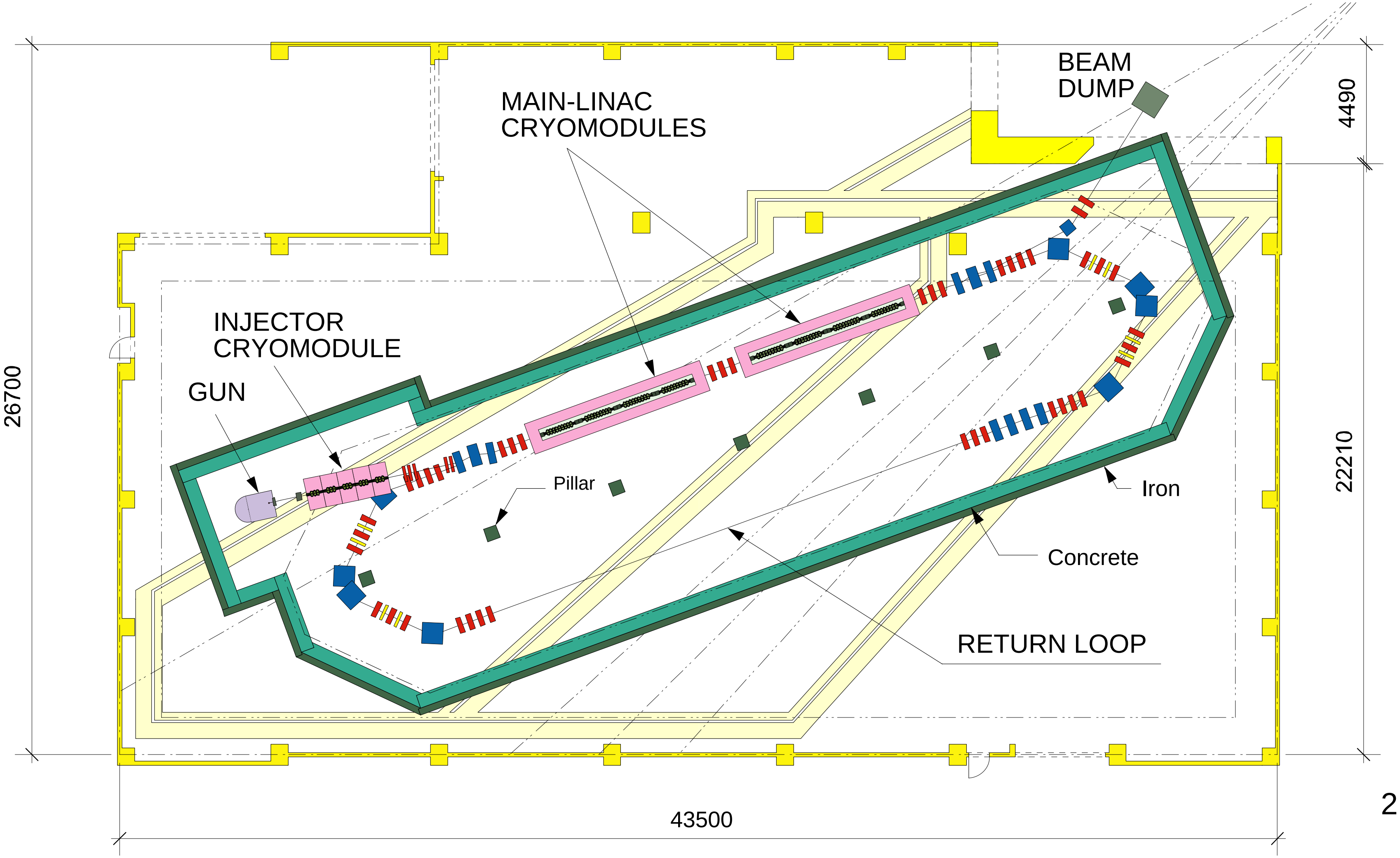
Mini-Workshop for ERL under the collaboration meeting between
CLASSE and KEK, March 12, 2007, at Cornell University

Planned ERL test facility

Cold neutron
building version

Maximum current: 100 mA
Beam energy: 60 – (200) MeV

Normalized emittance: 1 – 0.1 mm·mrad
Injection energy: 5 MeV (10-15 MeV)



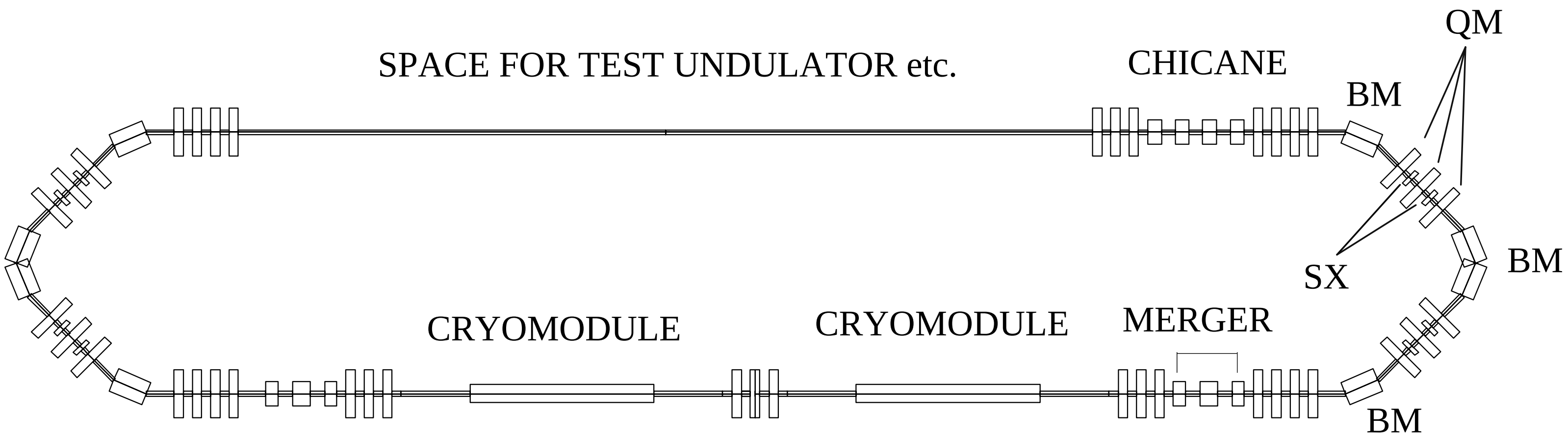
Beam dynamics issues

- Beam optics in the recirculation pass
  - Linear & non-linear optics issues
  - Bunch compression scheme
  - Collective effects due to CSR → not yet
- Beam instabilities *etc.*
  - BBU due to cavity HOMs → Sawamura's talk
  - Resistive-wall multibunch BBU
  - Ion trapping
  - Beam loss mechanism → not yet
- Injector simulations for design optimization
  - Multi-parameter optimization algorithms → under preparation

Beam optics in return loop

K. Harada, Y. Kobayashi (KEK)

Lattice under consideration (TBA)

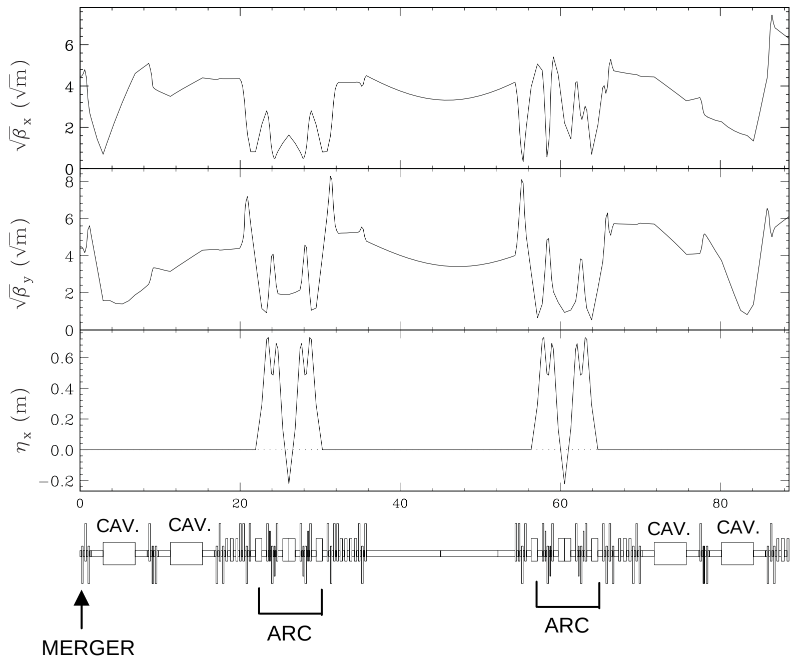


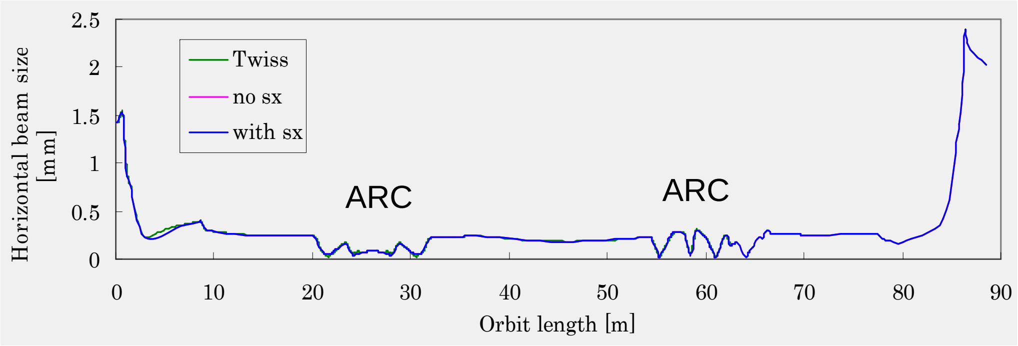
Design issues

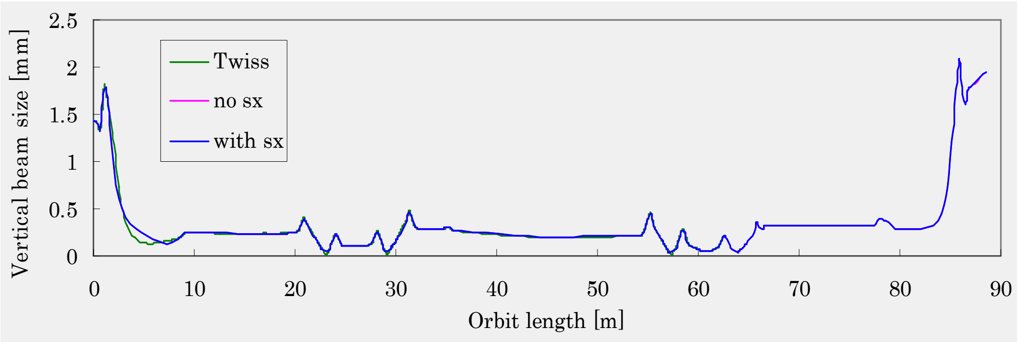
- Similar lattice to that of 5-GeV ERL.
- Minimize emittance growth due to CSR etc.
- Adjustable R_{56} for bunch compression (B.C.)
- Minimizing bunch length under B.C.
- Adjustable circumference for energy recovery
- x-y coupling control for BBU study
- Able to install undulators
- etc.

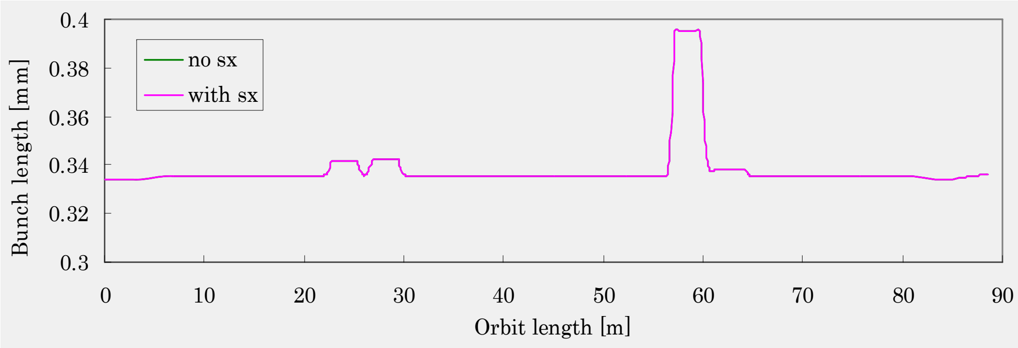
Linear optics and beam sizes (for recirculation)

On-crest acceleration (5 → 165 MeV) , σ_τ = 1 ps, $\sigma_E = 1\times10^{-4}$, $\varepsilon_{n(x,y)}$ = 1 mm·mrad, 20 MV/m×(4m)×2 modules.







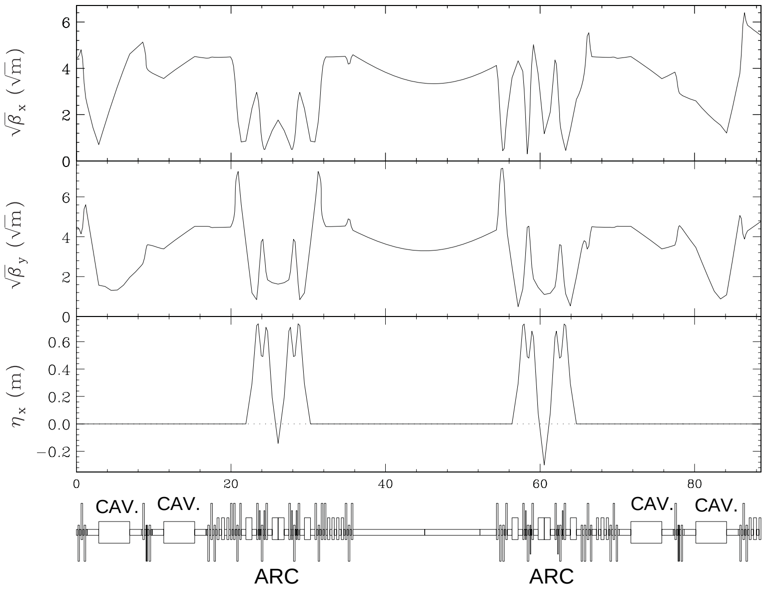


- Higher order aberrations are not dominant due to small energy spread.
- Negligible emittance growth and bunch lengthening.
- (CSR effects are not included)

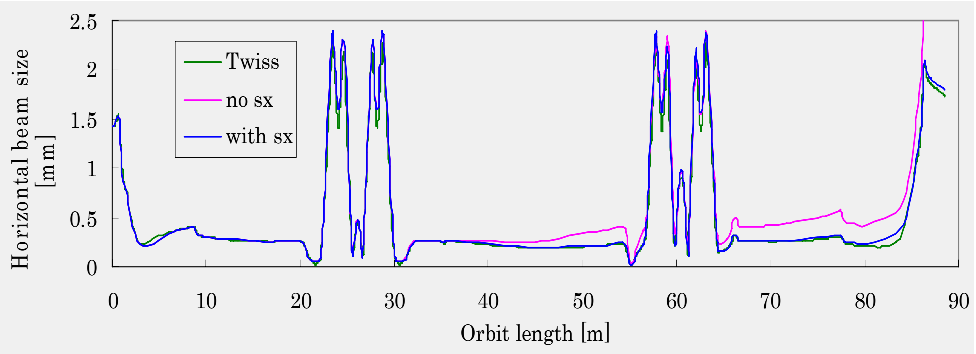
K. Harada (KEK)

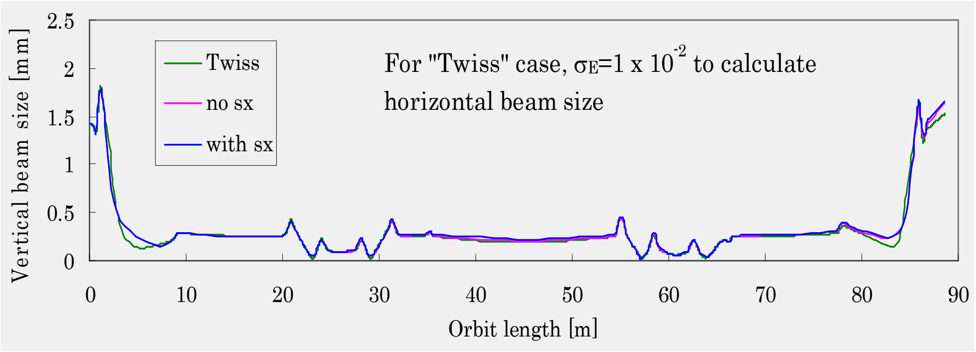
Linear optics and beam sizes (for B.C.; preliminary)

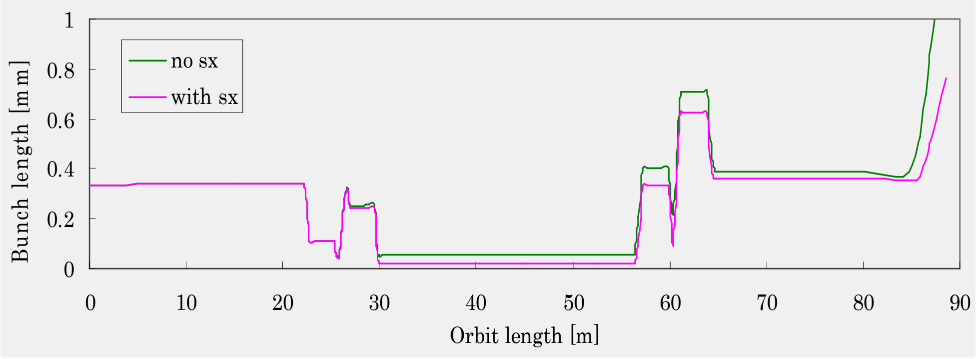
Off-crest acceleration ϕ=70 deg. (5 $\rightarrow$ 155 MeV) , σ_τ = 1 ps, $\sigma_E = 1\times10^{-4}$, $\varepsilon_{n(x,y)}$ = 1 mm·mrad



- Due to large correlated energy spread, chromaticity corrections are essential.
- The beam distribution has a halo, which will lead to beam losses. More optimization of beam optics is necessary.
- (CSR effects are not included)



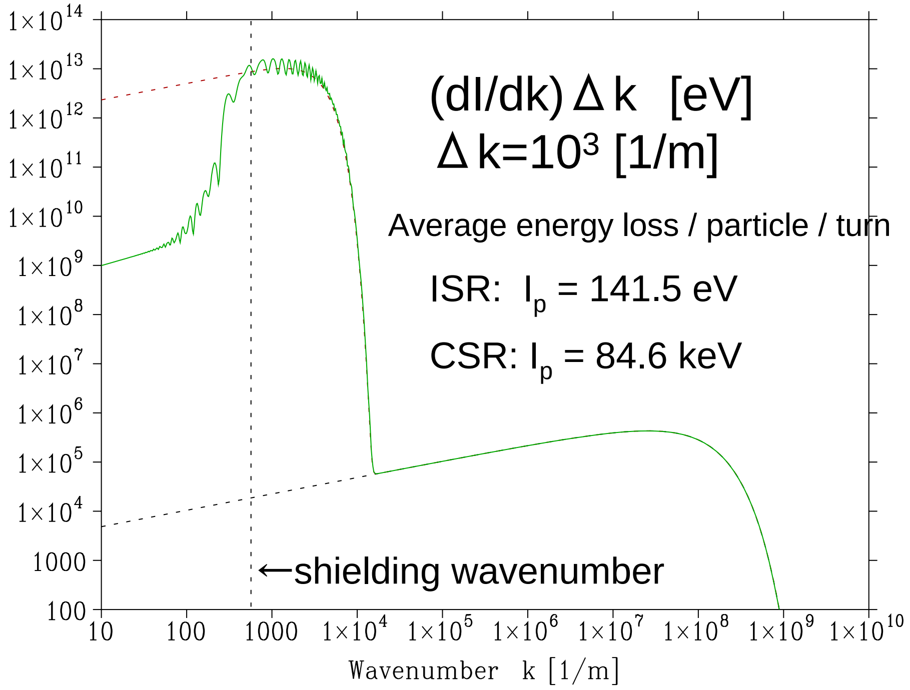




CSR in the Arcs

T. Agoh (KEK)

Radiation spectrum



$(dI/dk)\Delta k$ [eV]

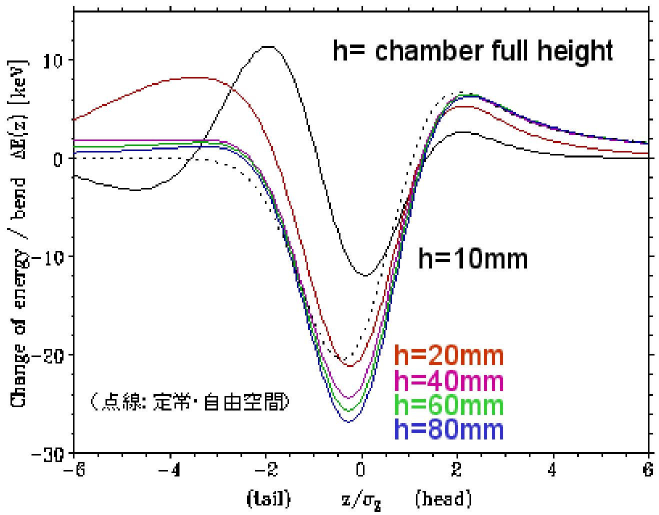
$\Delta k=10^3$ [1/m]

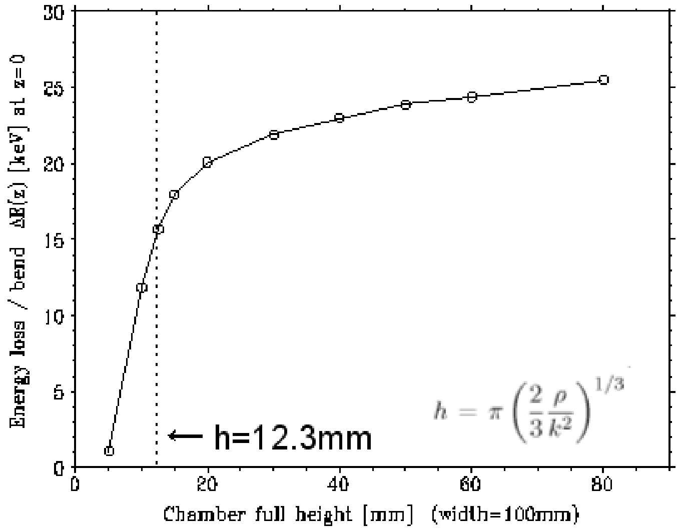
Average energy loss / particle / turn

ISR: I_p = 141.5 eV

CSR: I_p = 84.6 keV

Shielding effect (using mesh code)





E = 200 MeV

eN_e=77 pC ($N=4.8\times10^8$)

σ_τ=1 ps (Gaussian distribution)

Bend: ρ = 1m, 60 deg.×6

Vac.chamber: 100mm×40mm (Cu)

Resistive-wall multi-bunch BBU

N. Nakamura
(Univ. Tokyo)

- Resistive-wall wakes due to vacuum chambers may cause transverse beam breakup instability.
- Transverse RW wake depends strongly on the aperture:
  - An important factor for determining the aperture.
- Growth times were estimated analytically using simplified model.

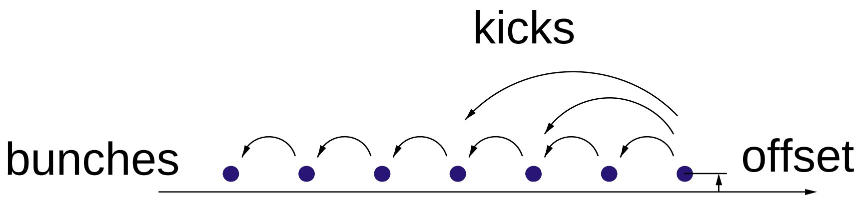
$$\boxed{W_\perp \propto \frac{1}{b^3}}$$

Transverse kick of resistive-wall wake

- Kick angle due to resistive-wall wake per bunch

$$\Delta\theta_y = -\frac{e^2N}{E}W_\perp \cdot y = \frac{e^2N}{E}\cdot\frac{cL}{\pi b^3 z^{1/2}}\sqrt{\frac{Z_0}{\pi\sigma_c}}\cdot y$$

N: Number of electrons per bunch E: Beam energy



Equation of motion

Equation of motion for an particle in the M-th bunch

$$y_M''(s) + k_y^2 y_M(s) = \sum_{N=0}^{M-1} S(M-N)\, y_N(s)$$

$$S(M) = \frac{a}{\sqrt{M}}, \quad a \equiv \frac{e^2N}{E}\cdot\frac{c}{\pi b^3 (c\tau_B)^{1/2}}\sqrt{\frac{Z_0}{\pi\sigma_c}} = \frac{4I_B}{I_A}\frac{\delta_{skin}}{b^3}$$

$$I_B = \frac{eN}{\tau_B}, \quad I_A = \frac{4\pi\varepsilon_0 mc^3\gamma}{e}, \quad \delta_{skin} = \sqrt{\frac{\tau_B}{\pi\mu_0\sigma_c}}$$

τ_B: bunch separation in unit of seconds k_y: external focusing
s: position of resistive-wall pipe, s=0 at the entrance

Asymptotic solution for $M \to \infty$ ($M \sim t/\tau_B$)

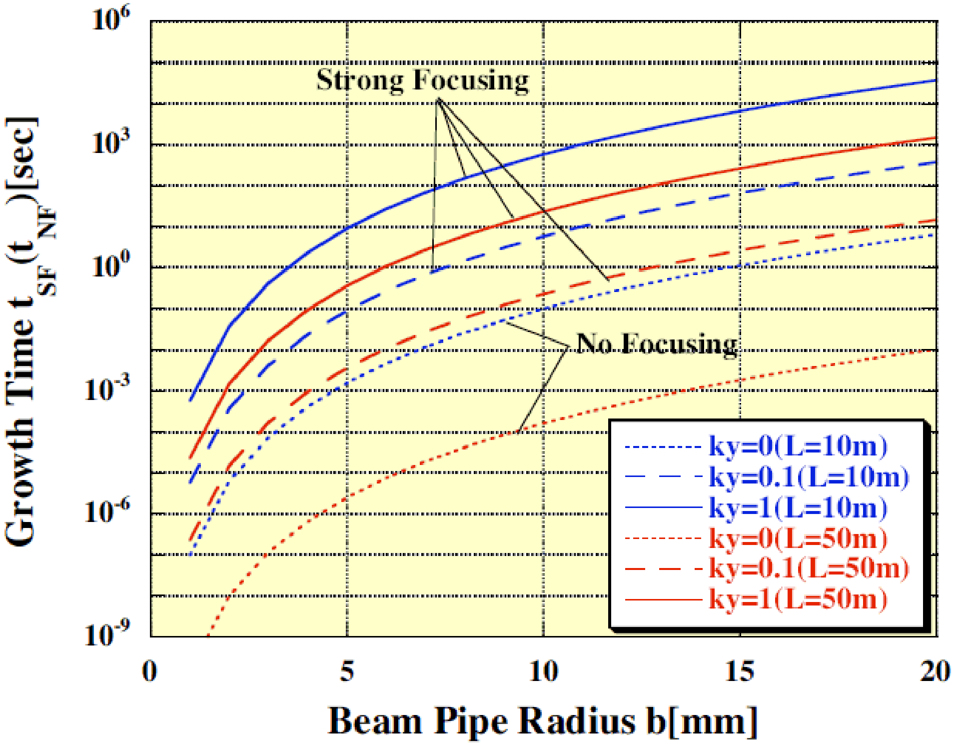
(J. M. Wang and J. Wu, PRST-AB 7, 034402(2004))

Resistive-wall multi-bunch BBU

Results of SF case (1)

N. Nakamura
(Univ. Tokyo)

Growth Time of Strong Focusing(SF) Case



$t_{SF} \propto k_y^2 b^6 L^{-2}$ ($t_{NF} \propto b^6 L^{-4}$)

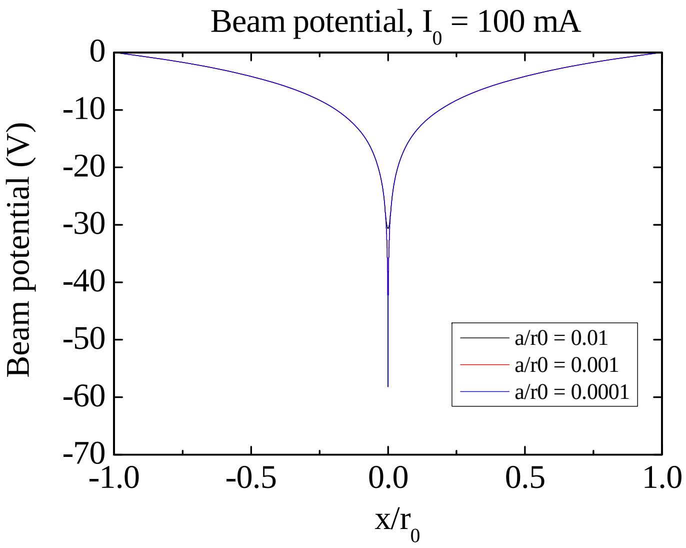
- E = 200 MeV, I_0 = 100 mA
- Wall material: aluminum

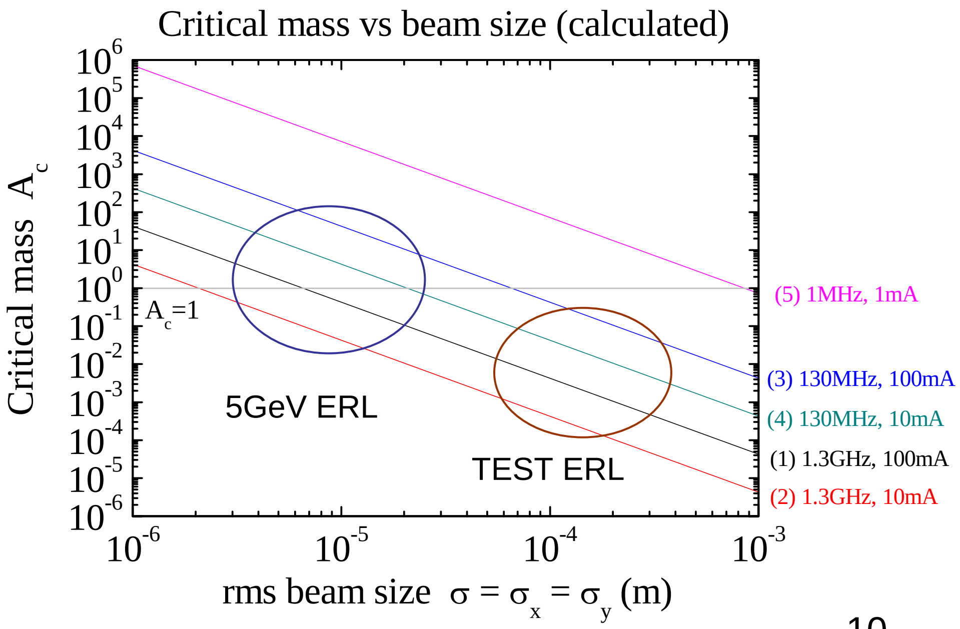
- Some feedbacks may be required for suppressing the instability.
- Simulation study is underway under more realistic situation.

Ion trapping

S. Sakanaka (KEK)

- Ion trapping may cause large betatron-phase errors or fast ion instabilities.
  - Ref: G. Hoffstaetter, M. Liepe: Nucl. Instrum. Methods A **557** (2006) 205.
- Cures should be considered in advance.
  - Clearing electrode (in above ref.)
  - Bunch gap (not promising?) → investigated further
  - Beam-size modulation



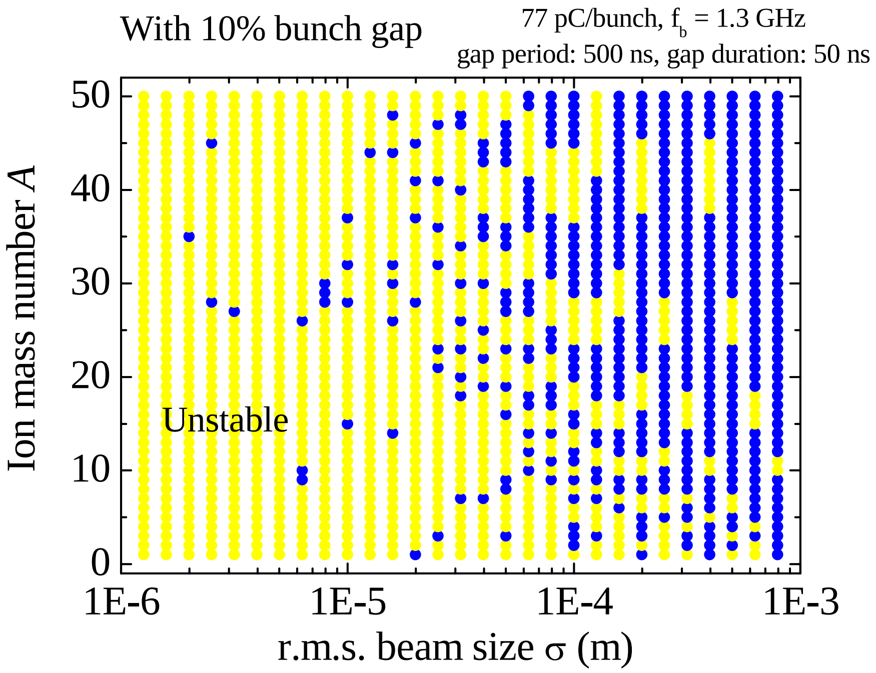


Effect of bunch gap (ion trapping)

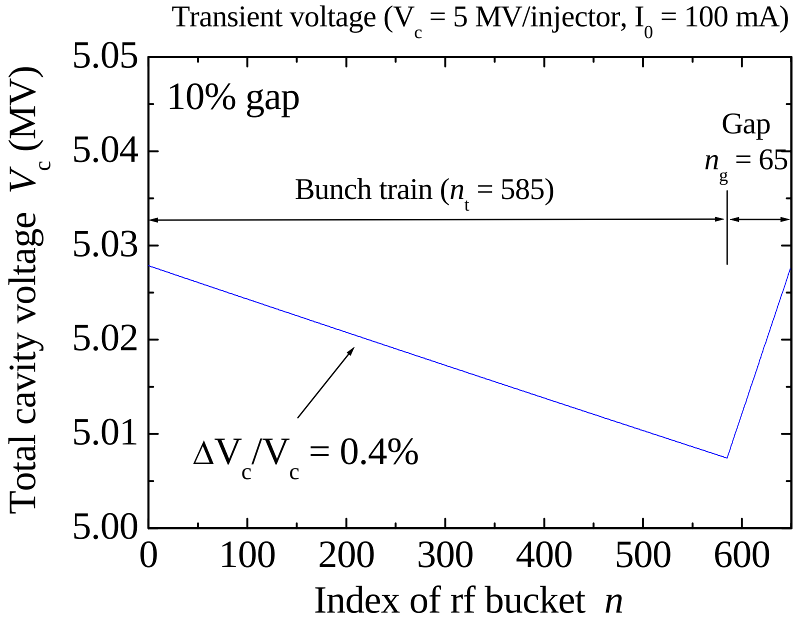
S. Sakanaka (KEK)

- Bunch gap with high repetition frequency: 2 MHz, 10% gap
- Assumed five 2-cell cavities, R_{sh}/Q = 200 Ω/cavity, V_c=5 MV, 100 mA
- Transient voltage variation may be acceptable:
- Feedforward compensation seems possible.

$$\frac{\Delta V_c}{V_c} \approx \frac{\omega_{res}(R_{sh}/Q)q_b}{2V_c}\frac{n_t n_g}{n_p}$$



Stability of ions

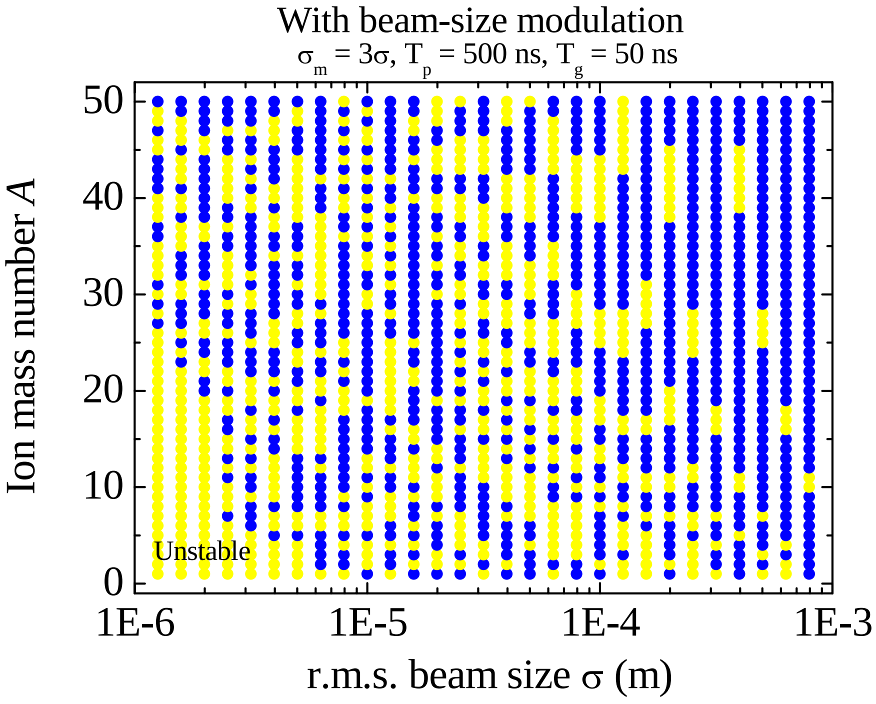


Bunch gap transient

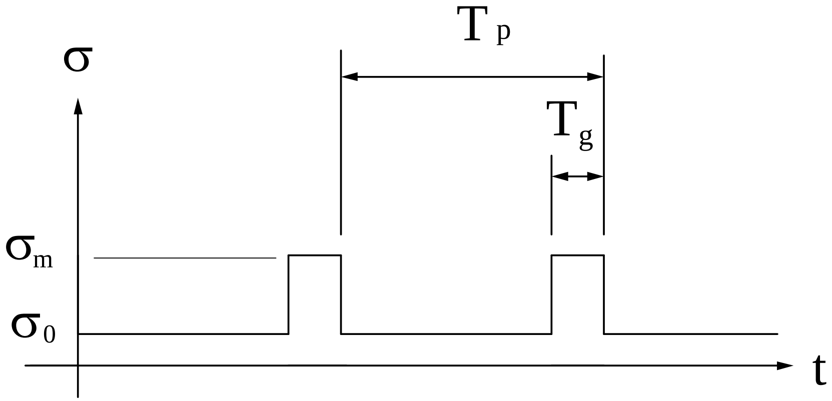
Effect of beam-size modulation

S. Sakanaka (KEK)

- Beam size modulation will result in the similar effect to the bunch gap.
- No rf transients in the injector cavities.
- Example of modulation: $\sigma_m = 3\times\sigma_0$, 10% duty factor, 2 MHz repetition.



Stability of ions



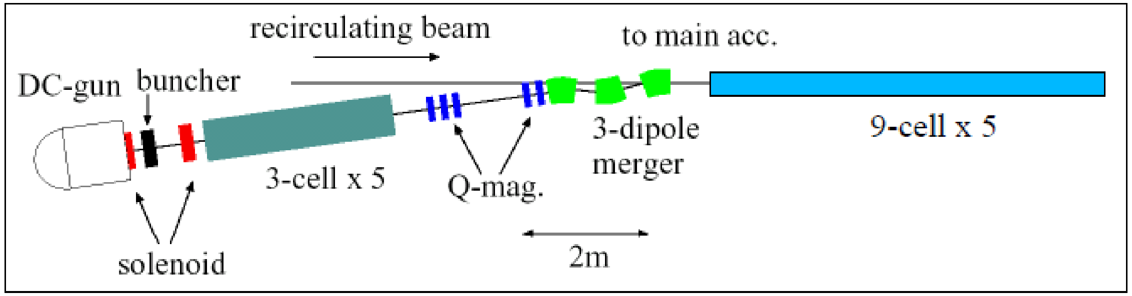
Beam size modulation

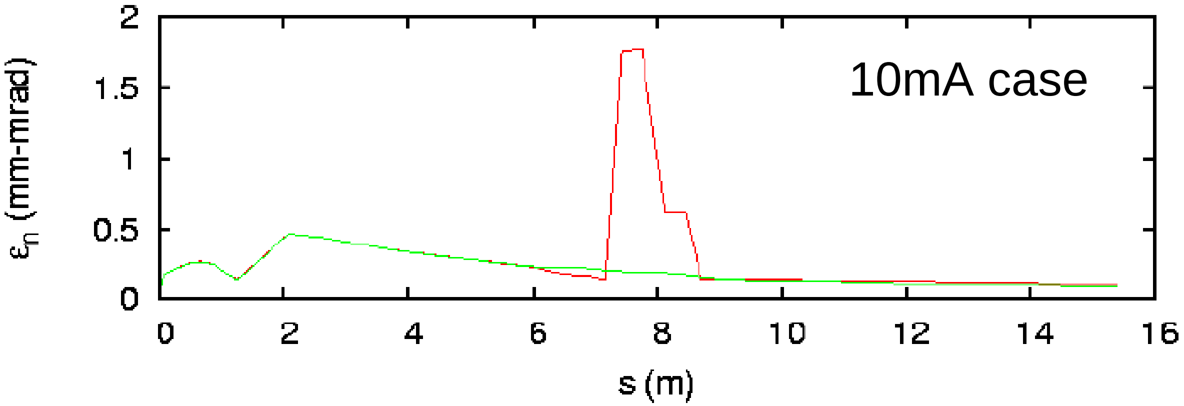
Starting point for injector design

Design made by JAEA group

R. Hajima et al., NIM-A557, 103-105 (2006)

Gun voltage : 500kV
Injection energy: 5MeV





Multi-parameter optimization with sumulated annealing (SA) and downhill symplex algorithms.

Simulation result (ε_n)
1mm·mrad (100mA)
0.1mm·mrad (10mA)

Further optimization is underway by referring Cornell design

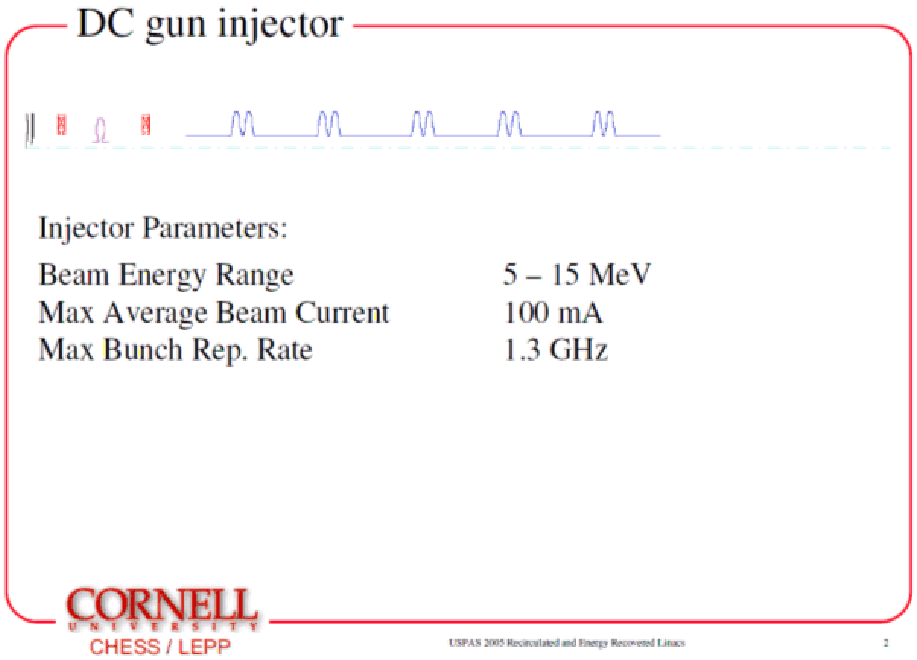
ε_n ~ 0.1 mm·mrad (~100 mA; 0.1 nC/bunch)

(cf.) I.V. Bazarov and C.K. Sinclair, Phys. Rev. ST Accel. Beams **8**, 034202 (2005).

Toward further optimization

Reproduction of Cornell simulations (Astra)

T. Miyajima (KEK)



DC gun injector

Injector Parameters:

Beam Energy Range	5 – 15 MeV
Max Average Beam Current	100 mA
Max Bunch Rep. Rate	1.3 GHz

USPAS 2005 Recirculated and Energy Recovered Linacs 2

Configurations

- DC photocathode
- Solenoid + buncher + solenoid
- Five 2-cell cavities
- 80 pC/bunch
- Without any quadrupoles
- 8.56 m to exit

Courtesy: Dr. I. Bazarov.

- ε_{nx} = 1.11 mm·mrad (Cornell: 0.82) at gun voltage of 500 kV
- ε_{nx} = 0.29 mm·mrad (Cornell: 0.14) at gun voltage of 750 kV
- Scripts of the optimization algorithms are under preparation.

Toward further optimization

Dependence of emittance on the first-cavity voltage

T. Miyajima (KEK)

Case (1)

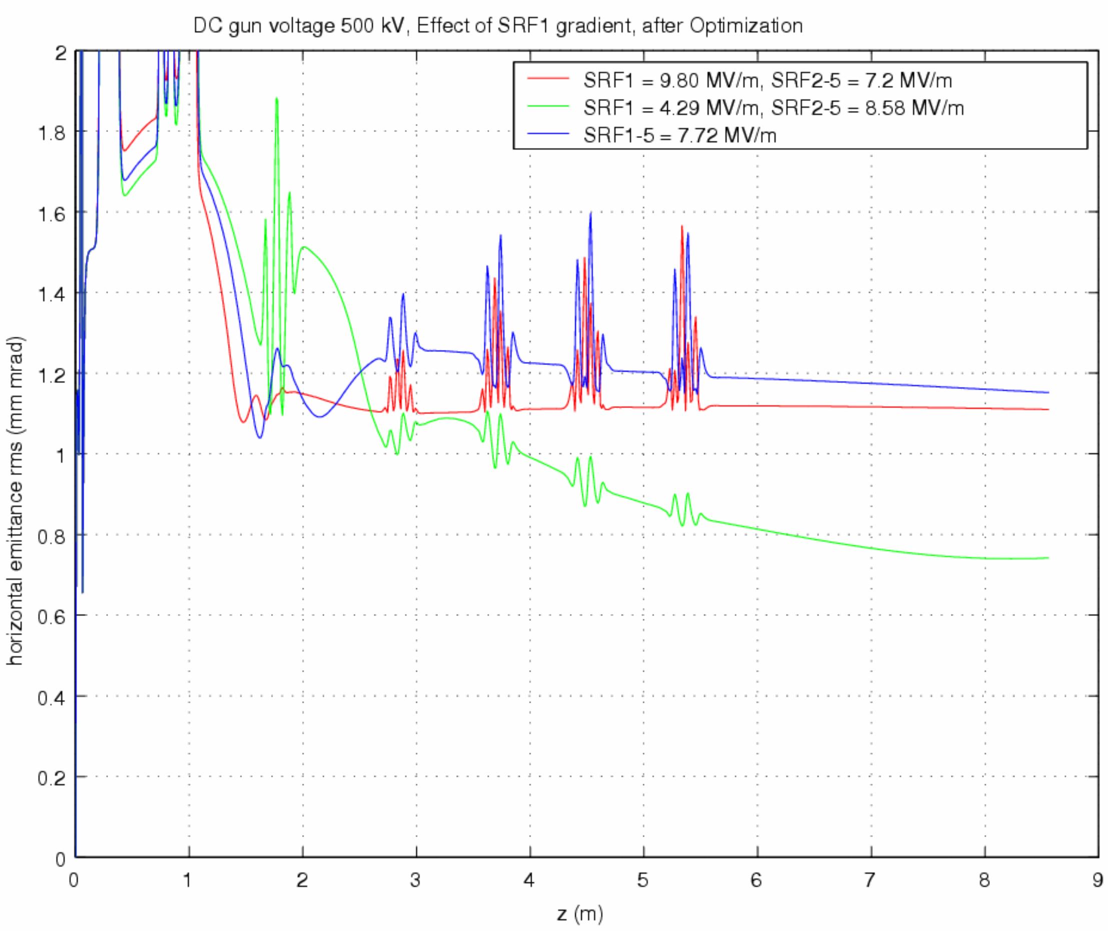
- SRF1 = 9.80 MV/m, SRF2-5=7.20 MV/m
- ε_{nx} = 1.11 mm·mrad

Case (2)

- SRF1 = 4.29 MV/m, SRF2-5=8.58 MV/m
- ε_{nx} = 0.74 mm·mrad

Case (3)

- SRF1-5 = 7.72 MV/m,
- ε_{nx} = 1.15 mm·mrad



Low rf voltage of the first cavity yielded a lower emittance.

Injector issues to be investigated

Suggestions about the following issues are very welcome.

- Requirement for Q-values of HOMs at injector SC cavities.
  - Simulation study is under consideration.
  - Are there any studies at Cornell?
- Contribution of each effect to the emittance growth.
  - Space charge, RF kicks, CSR at merger *etc.*
  - Is it possible to understand each effect separately ?
  - What are the key issues?
- Constitution of the power source.
  - Is it acceptable to drive several cavities by a single klystron?
- Other potential (might be minor) causes for beam degradations.
  - Wakefields in the gun chamber
  - Wakefields at the beam collimator for removing beam tails
  - Ion trapping, *etc.*

Summary

- Lattice design & single-particle optics calculations for the ERL test facility
  - Need more optimizations
  - Collective effects due to CSR are not included yet
- Prediction of HOM-BBU thresholds (Sawamura's talk)
  - For newly designed ERL cavity & for TESLA cavity
  - Very promising
- Investigation on the resistive-wall multibunch BBU
  - Simulation study is underway
- Possible cures for ion trapping
- Preliminary design of injector.
  - Need much optimizations.
  - Suggestions are very welcome