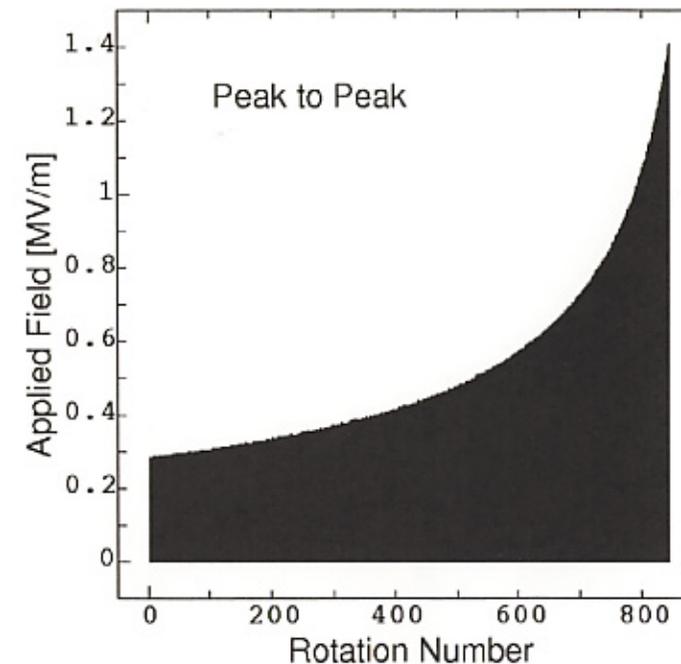
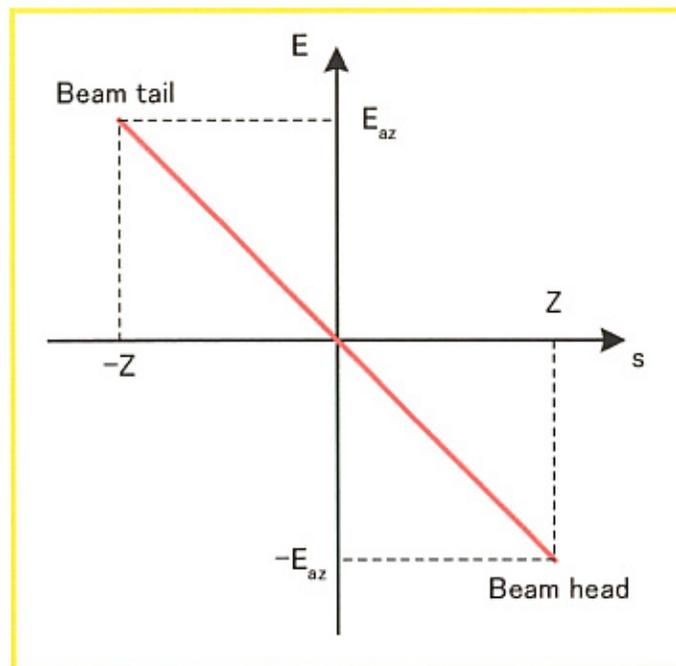


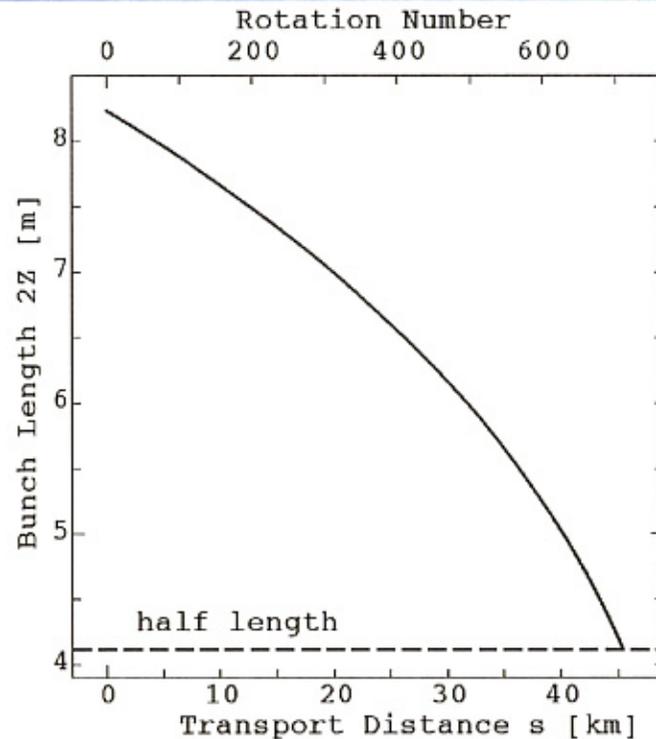
Change of the Applied Voltage

Applied electric field (peak to peak) during rotation number

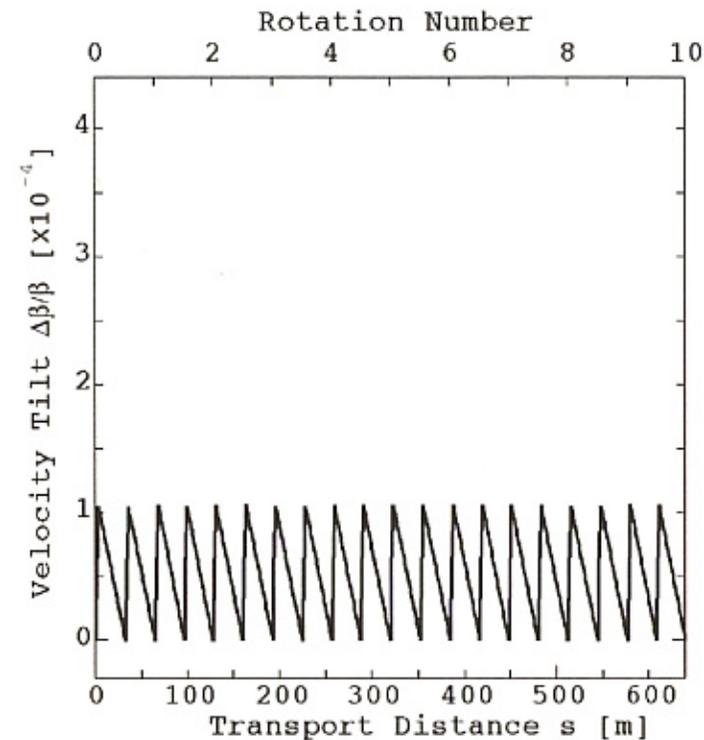


Applied electric field increase is required with bunch compression, because self-repulsion force of beam also increases during compression.

Beam Longitudinal Dynamics



Bunch length as a function of rotation number in the recirculator



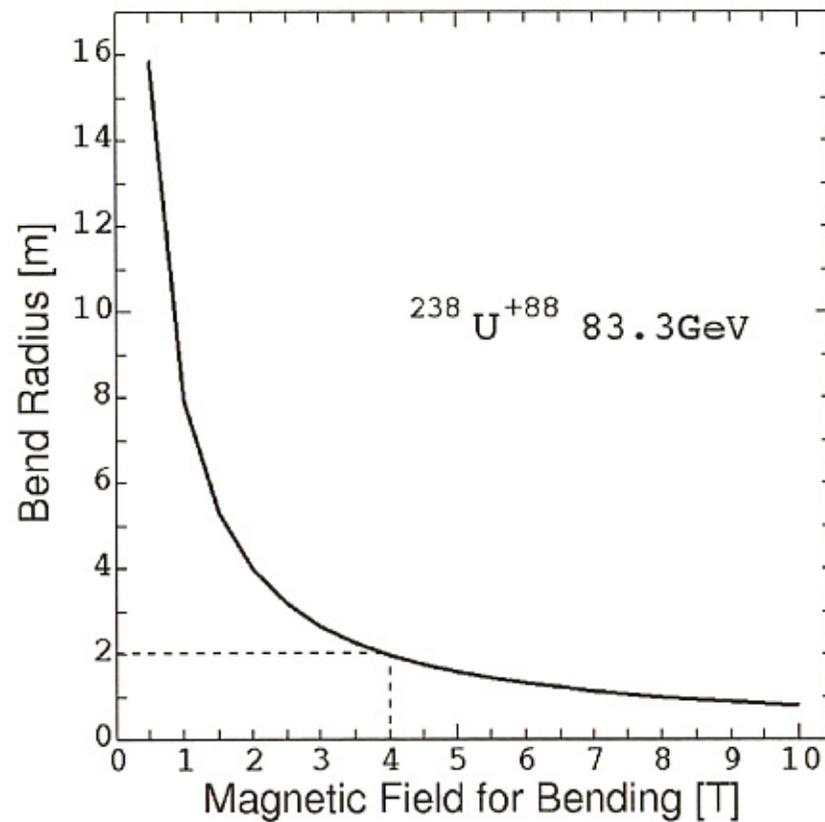
Bunch length and velocity tilt vs. rotation number



Beam Bunch is gradually Compressed during Recirculation

Estimation of Bending Magnet Requirements

Required radius for beam bending at the magnetic field



Bend radius ρ is calculated by:

$$\rho = \frac{\gamma m \beta c}{q e B}$$

e.g.

$$B = 4\text{T} \quad \blacktriangleright \quad \rho = 2\text{m}$$

▶ Recirculating Buncher with Quasi-equilibrium Compression



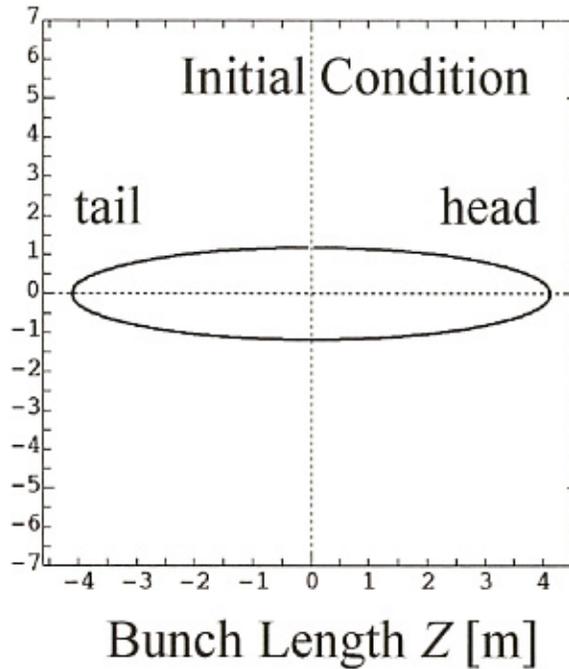
Long time recirculation is required.



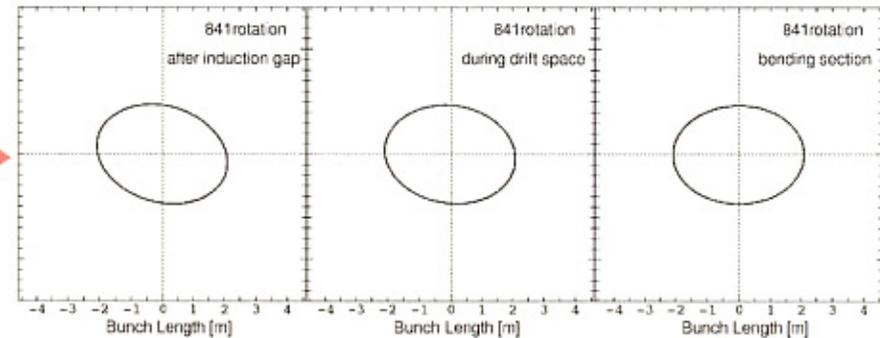
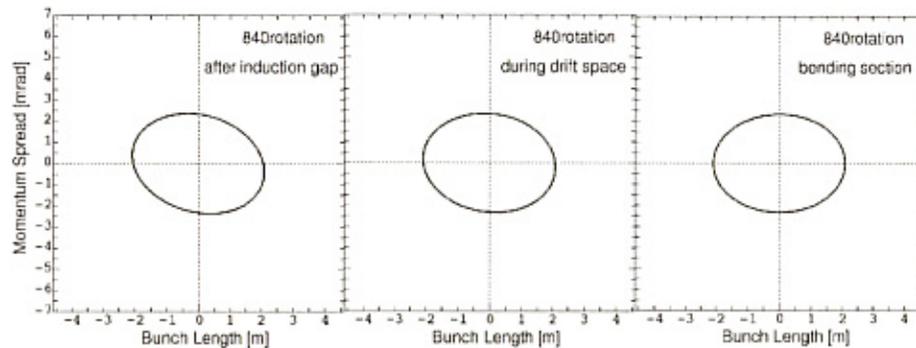
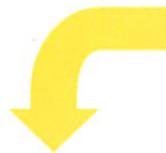
- *Emittance Growth* due to quadrupole lattice misalignment
- *Beam Particle Loss* due to residual gas interaction
- *Dispersion Increase* due to small bend radius

Bunching Process on Longitudinal Phase Space

Momentum Spread $\Delta p/p$ [mrad]

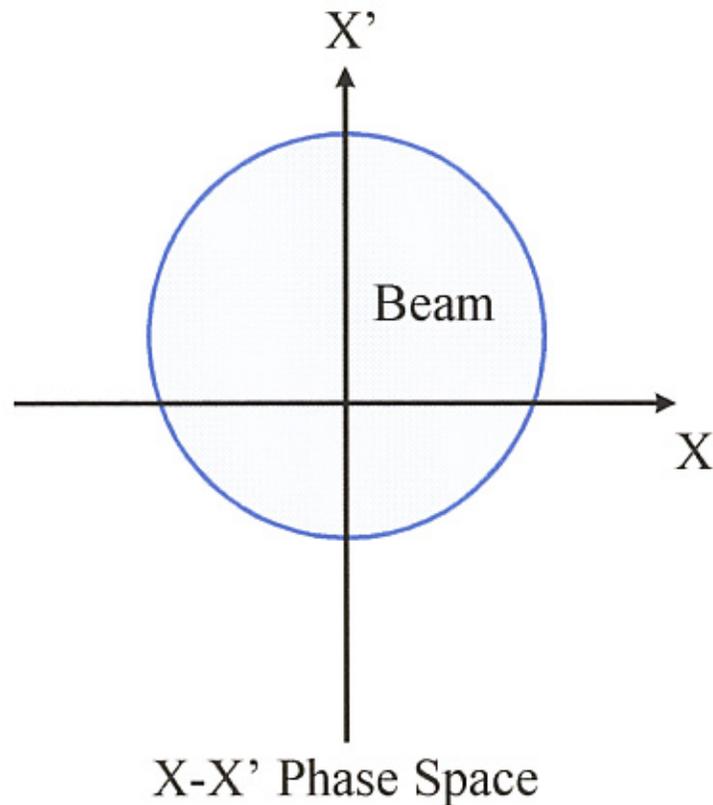


Longitudinal bunch envelope on phase space at initial condition



Longitudinal Beam Envelope on Phase Space during Beam Compression

Transverse Emittance Growth by off-centered beam



Centroid misalignments increase emittance.

If lattice error is δx_{rms} ,

emittance growth is estimated by*

$$\delta \varepsilon_{nt} \approx 4 \beta C_{rw} \frac{\sigma_0^2}{\sigma} \left(\frac{\delta x_{rms}}{S} \right)^2 ds$$

σ & σ_0 : Phase advance with & without space charge

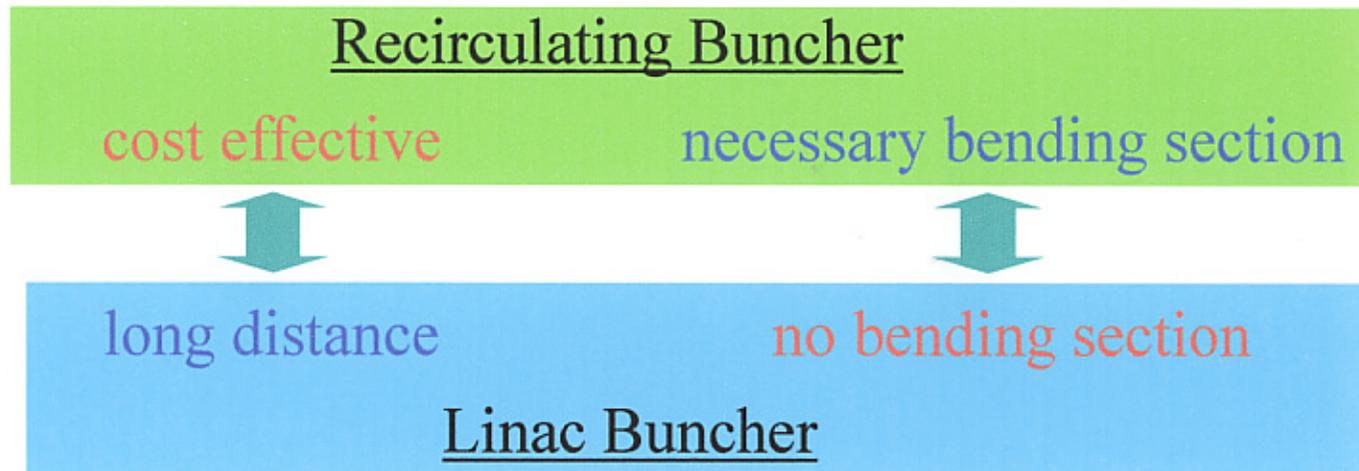
S : Lattice period length

C_{rw} : Ratio of centroid position to transited error

*M. Reiser, J. Appl. Phys. **70**, 1919 (1991).

J.J. Barnard, *et al.*, Phys. Fluids **B 5**, 2698 (1993).

Selection of Buncher Type



Trade-off of Linac & Recirculator

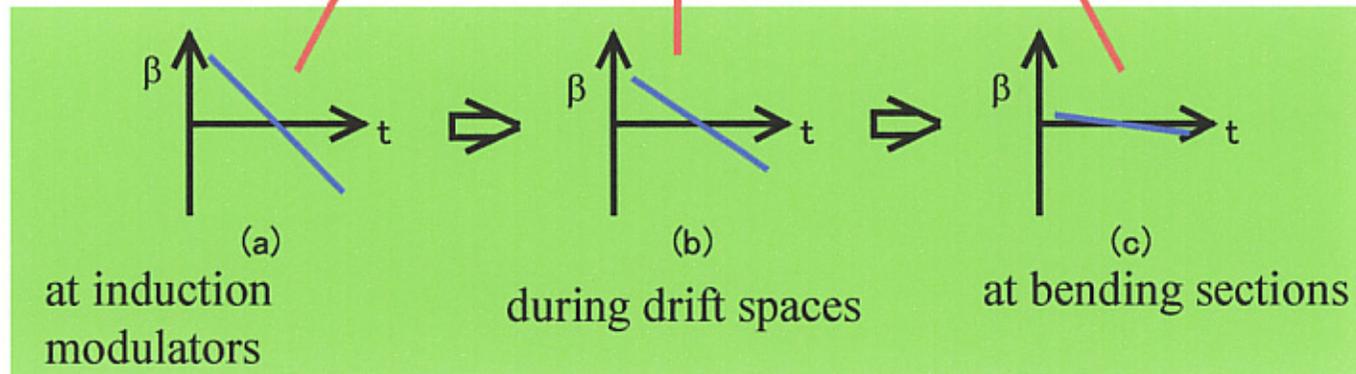
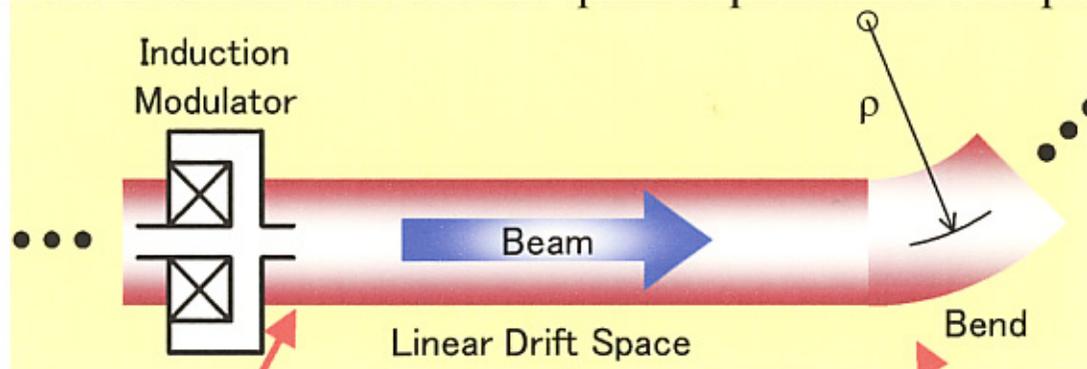
If
▶ **Bunching by $\Delta\beta/\beta$ & Bending without $\Delta\beta/\beta$**
are possible,

Recirculating Beam Buncher with Quasi-Equilibrium Compression*

*T. Kikuchi, M. Nakajima, and K. Horioka, J. Plasma Fusion Res. **78**, 1 (2002).
T. Kikuchi, M. Nakajima, and K. Horioka, Phys. Plasmas **9**, 3476 (2002).

The Concept

One unit of beam buncher for quasi-equilibrium compression



Transition of $\Delta\beta/\beta$ along the beam buncher

Applied velocity tilt at induction modulator is canceled due to self-repulsion force of beam, so that beam can be transported without velocity tilt during bending section.

Balance Equation

Estimation of minimum bunch length with quasi-equilibrium compression

$$\frac{d^2 z_m}{ds^2} = -k_z' + \frac{K_L}{z_m^2} + \frac{\varepsilon_{zz'}^2}{z_m^3}$$



$$\frac{dz_m}{ds} = -\int_{t_g} k_z' ds + \int_{s_g} \left(\frac{K_L}{z_m^2} + \frac{\varepsilon_{zz'}^2}{z_m^3} \right) ds = 0$$

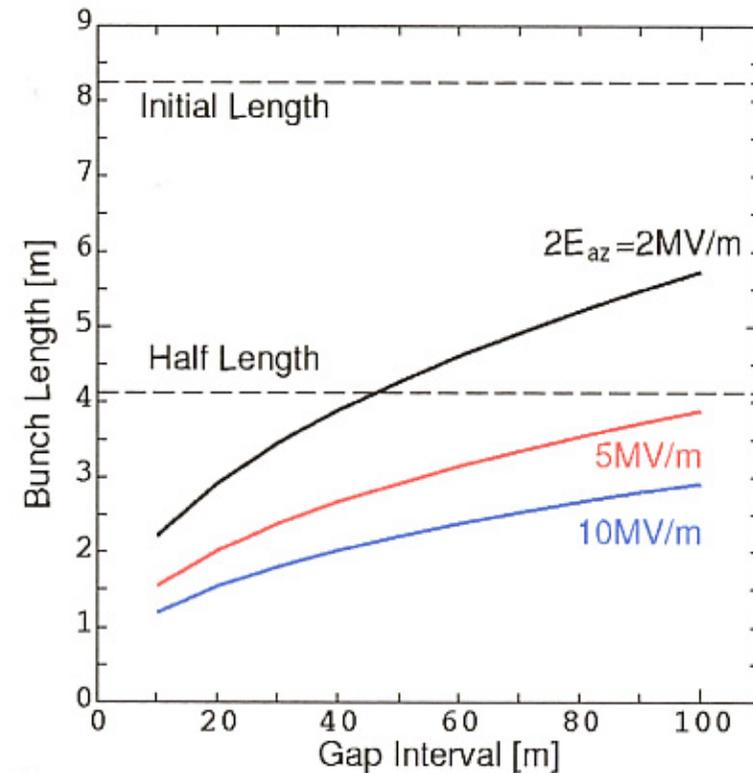
Balance Equation



$$k_z' d_g Z_b^3 - K_L S_g Z_b - \varepsilon_{zz'}^2 S_g = 0$$

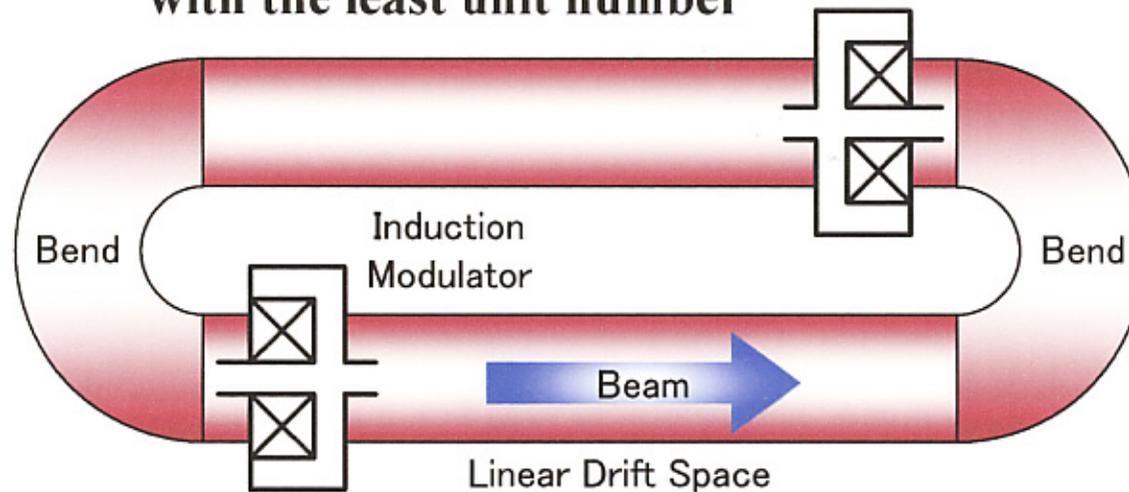


Balanced beam length is estimated under recirculating buncher with quasi-equilibrium compression.



Example

Recirculating buncher configuration with the least unit number



Repulsion force almost always balances to bunching force during compression,
i.e. beam is gradually compressed under the quasi-equilibrium condition.

$$\frac{d^2 Z}{ds^2} = -k_z' + \frac{K_L}{Z^2} + \frac{\varepsilon_{zz'}^2}{Z^3}$$

Longitudinal Envelope Equation

Problems of RIKEN Buncher

Several problems are as follows:

1. small site area (short accelerator length)
2. required voltage (applied electric field) for beam compression
3. large head-to-tail velocity tilt

etc.

Especially...

Beam Bending with Large Velocity Tilt

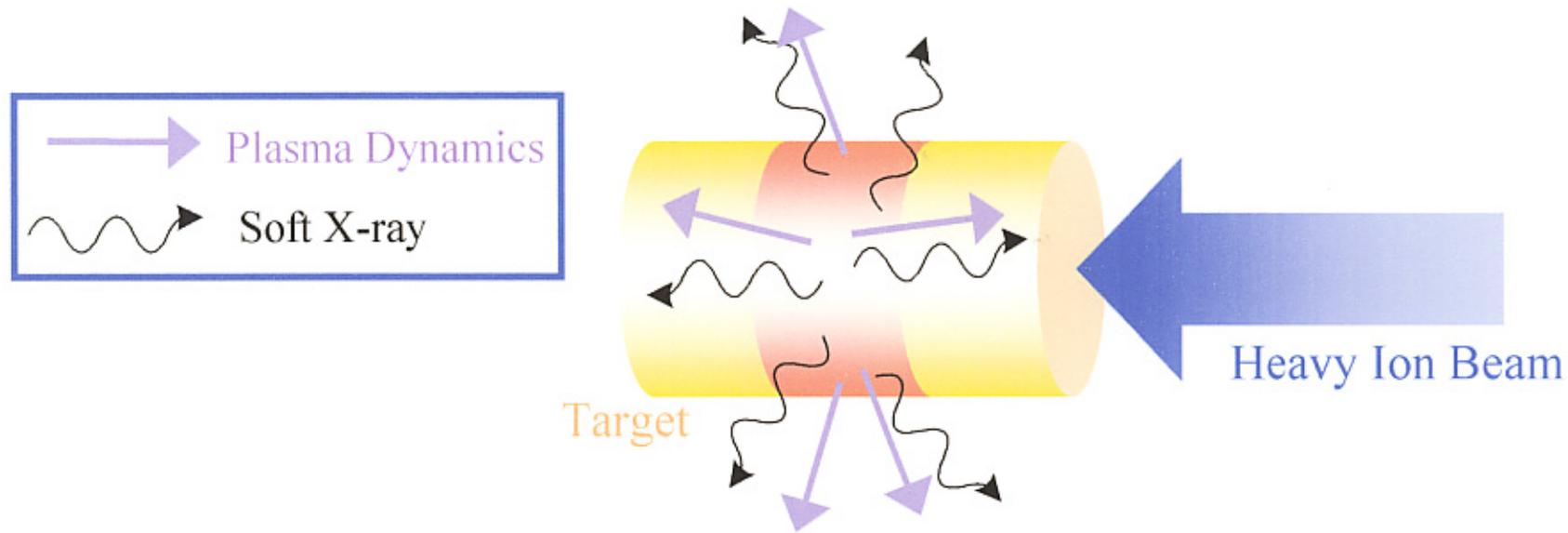
 **Difficult**

i.e. Beam radius is expanded due to bending magnet & large velocity tilt at bending section.

Parameters for RIKEN Buncher

Ion Species	$^{238}\text{U}^{88+}$
Ion Number	2.84×10^{11}
Pulse Duration	40 ns \Rightarrow 20 ns
Beam Current	100 A \Rightarrow 200 A
Total Charge	4 μC
<hr/>	
Particle Energy	350 MeV/u = 83.3 GeV ($\beta \sim 0.687$)
Bunch Length $2Z$	8.24 m \Rightarrow 4.12 m
Transverse Emittance	20 mm mrad
Longitudinal Emittance $\pi\varepsilon_{zz'}$	$2.18 \times 10^{-3} \pi \text{ m}\cdot\text{rad}$ ($\Delta P/P = 10^{-3}$)

 High-current & high-energy & short pulse heavy-ion beam



Heavy Ion Beam & Solid Target Interaction

For $k_B T = 35 \text{ eV}$
 $\eta_{\text{con}} = E_{\text{rad}} / E_{\text{dep}} = 30\%$ plasma generation (Au target),

beam parameters of 20 ns 350 MeV/u $^{238}\text{U}^{88+}$ 2.84×10^{11} particles
are needed.

M. Murakami, *et al.*, J. X-ray Sci. Technol. 2, 127 (1990).

Application, Comparative Study and Beam Physics Issues
in Recirculating Beam Buncher
with Quasi-equilibrium Compression

T. Kikuchi, M. Nakajima, and K. Horioka
Energy Sciences, Tokyo Institute of Technology

J. Hasegawa, Y. Oguri, and M. Ogawa
Res. Lab. for Nucl. Reactor, Tokyo Institute of Technology

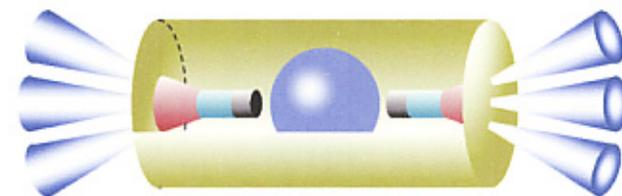
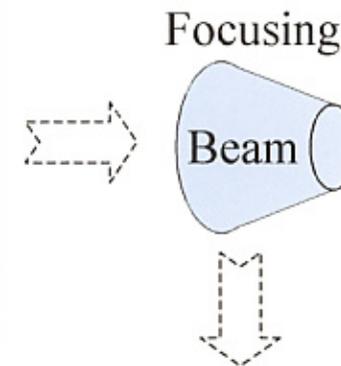
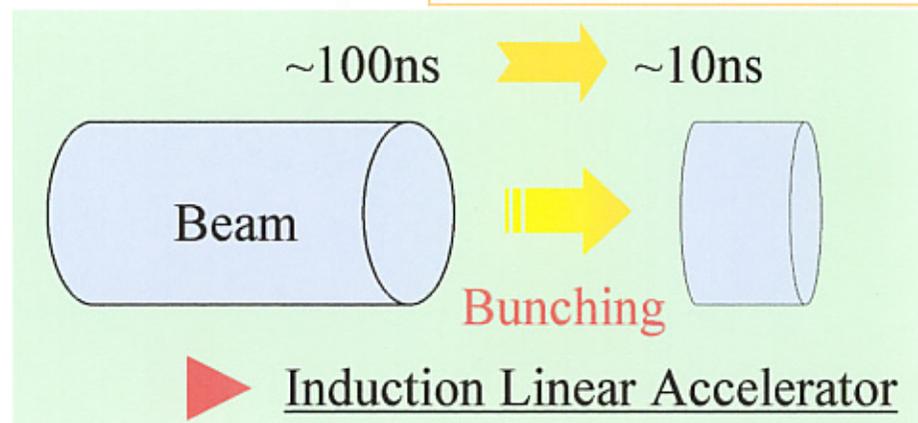
A. Sakumi and T. Katayama
RIKEN and Univ. Tokyo

International Workshop on Recent Progress of Induction Accelerators
(RPIA2002), October 29-31, 2002, Tsukuba, Japan

● Heavy Ion Inertial Fusion

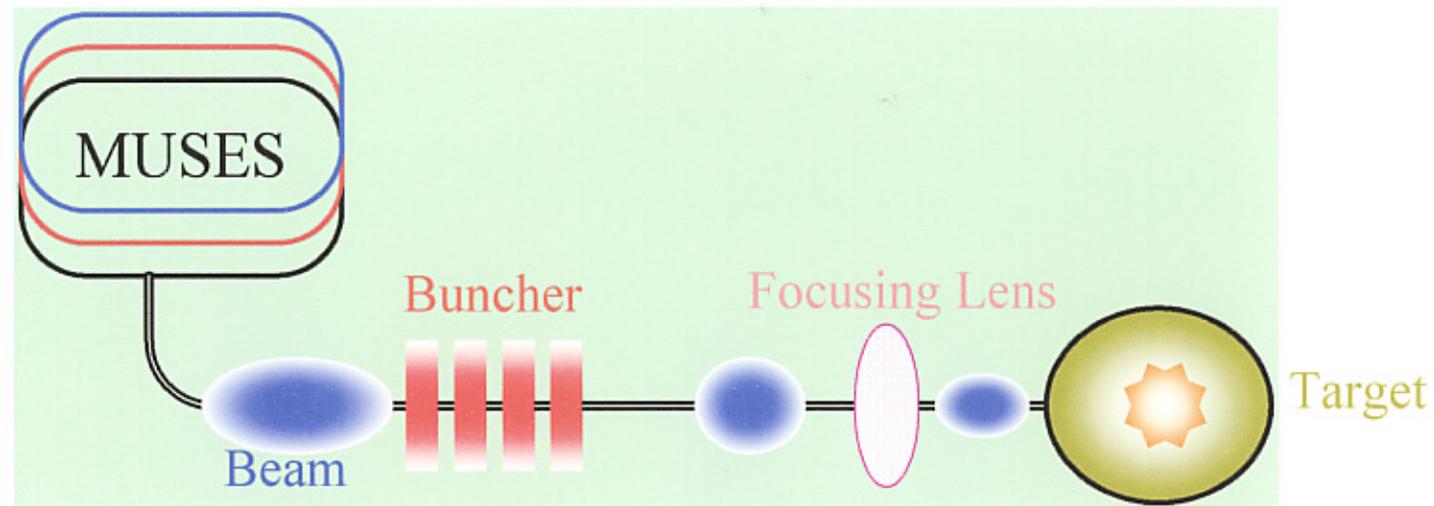
➡ Intense Heavy Ion Beam ($\sim 10\text{GeV}$ $\sim 10\text{ns}$ $\sim 100\text{kA}$)
Generation & Transport are required for effective implosion.

Accelerated Heavy Ion Beam ➡ Final Beam Bunching



Beam Irradiation for Implosion

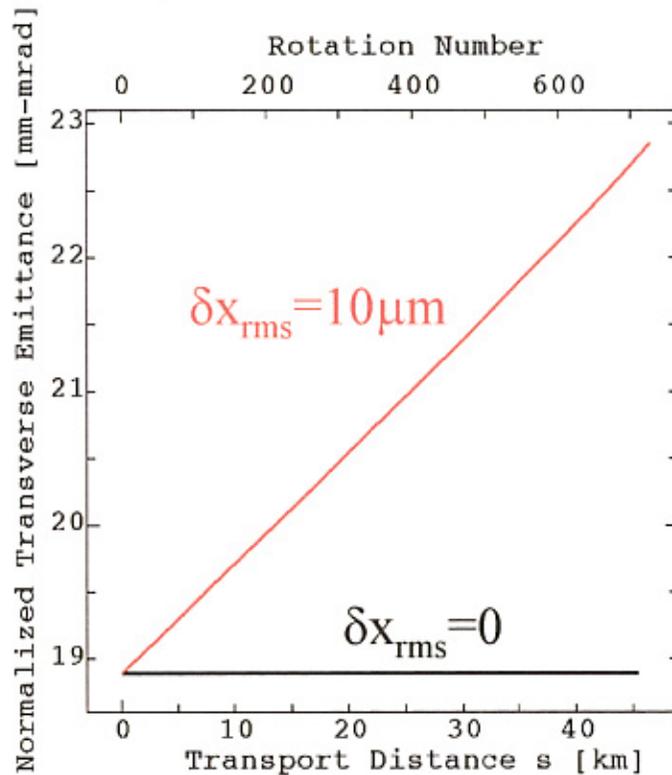
Proposal of Intense Heavy Ion Beam Buncher for HIF Target Experiment of RIKEN MUSES Project*



- Beam Compression using Induction Buncher
 - High-Current Beam Focusing by Plasma Lens
 - X-ray Conversion by Heavy Ion Beam Irradiation
- etc.

*T. Katayama, Fusion Eng. Des. **44**, 313 (1999).

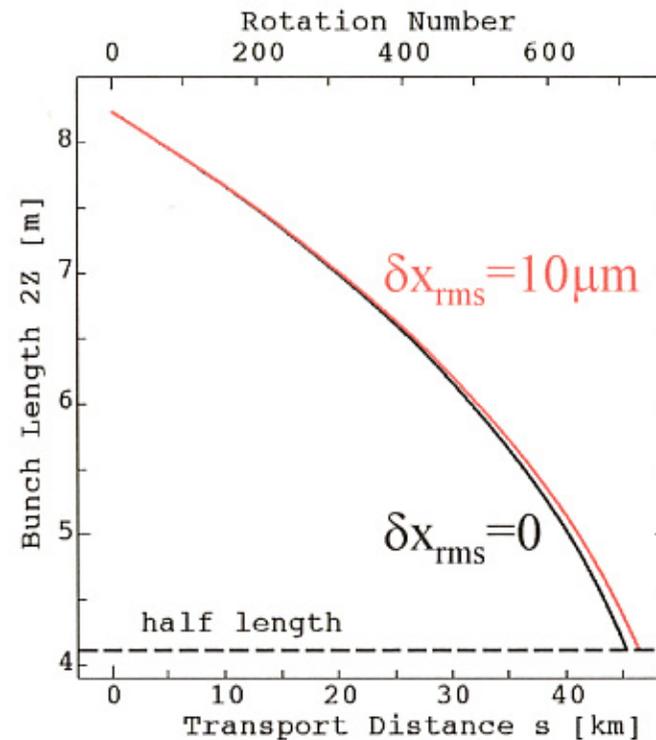
Beam Dynamics with Emittance Growth



Normalized Transverse Emittance Growth

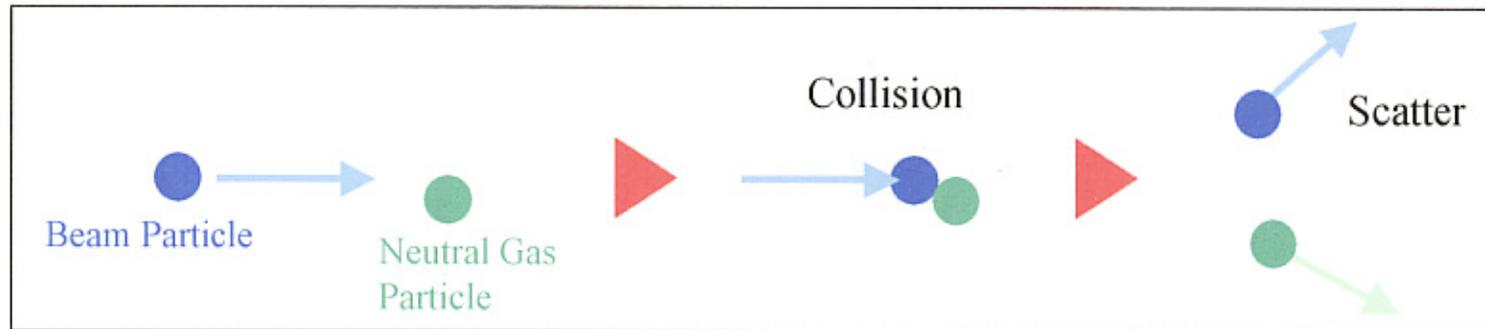


Emittance Growth Ratio ~ 1.2



Bunch Length Variation with and without error

● *Beam Particle Loss* due to residual gas interaction



Transmission Factor of Beam Particle

$$f_T = \exp\left\{-3.3 \times 10^{16} P_g (\sigma_L + \sigma_C) s\right\}$$

$$\text{Loss Cross Section : } \sigma_L \approx 9 \times 10^{-19} q^{-2/5} \beta^{-2}$$

$$\text{Capture Cross Section : } \sigma_C \approx 3 \times 10^{-28} q^{5/2} \beta^{-7}$$

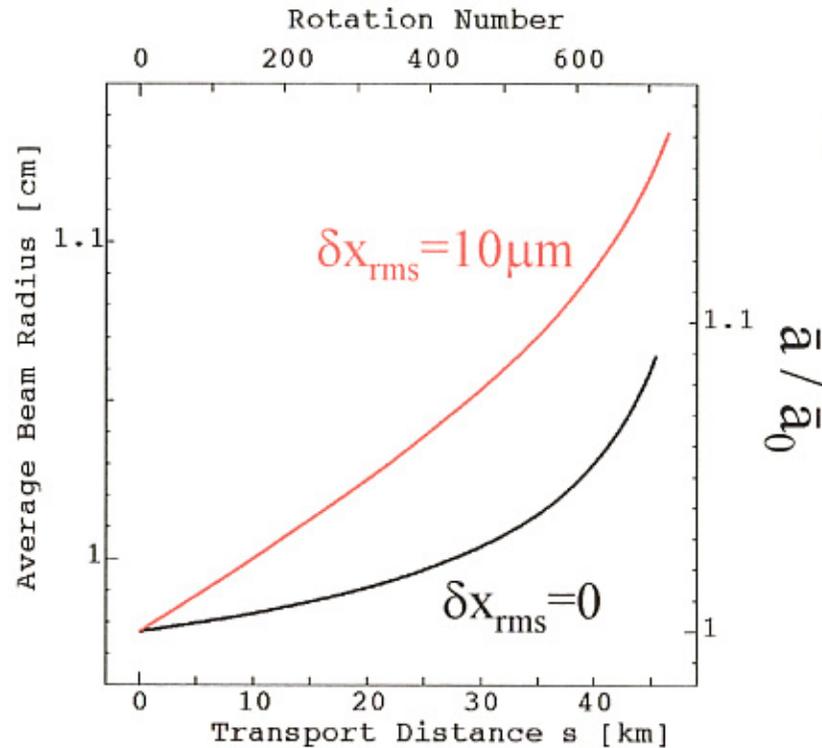


Fractional Beam Particle Loss is $\sim 8 \times 10^{-8}/\text{m}$ at $P_g = 10^{-10}$ Torr.

In high-power accelerator operations, $< 10^{-7}/\text{m}$ is required.*

*R.A. Jameson, *et al.*, Nucl. Instrum. Methods Phys. Res. B 68, 474 (1992).

Beam Radius Diffusion due to Emittance Growth



Beam Radius Diffusion Fraction

$\sim 9\%$ in $\delta x_{rms} = 0$

$\sim 16\%$ in $\delta x_{rms} = 10 \mu m$



Beam radius increases by emittance growth

Average Beam Radius during Rotation

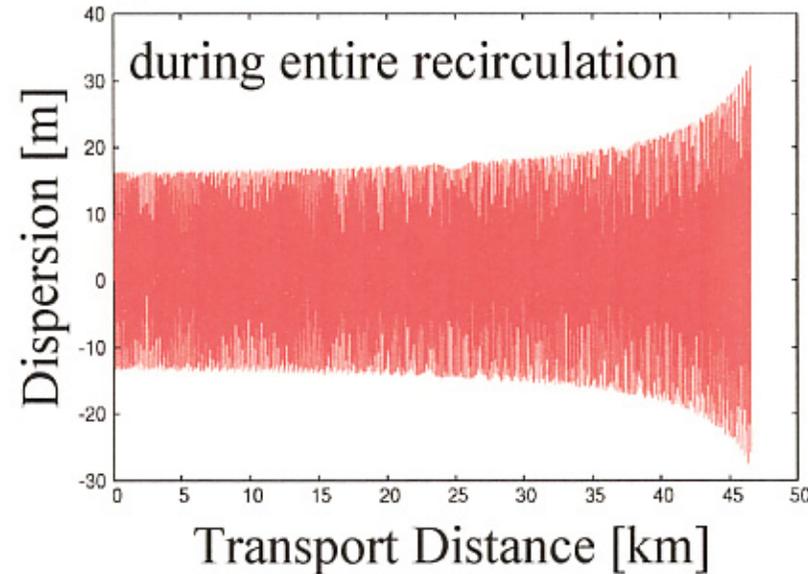
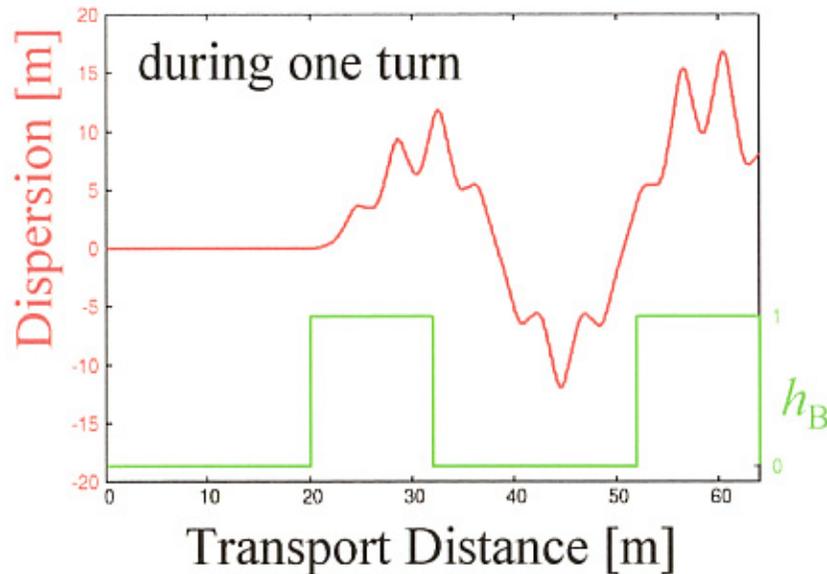
$$\bar{a}^2 = \frac{2\varepsilon_t L}{\sin\sigma}$$

Estimation for Dispersion Function

$$\frac{d^2 D}{ds^2} = - \left\{ k_t^2 h(s) - \frac{K}{\bar{a}} \right\} D + \frac{h_B(s)}{\rho}$$

D : Dispersion Function
 ρ : Bend Radius

in Racetrack Buncher Configuration



Dispersion Effect > Space Charge Effect (from Envelope Eq.)

Dispersion becomes large



Beam radius increase

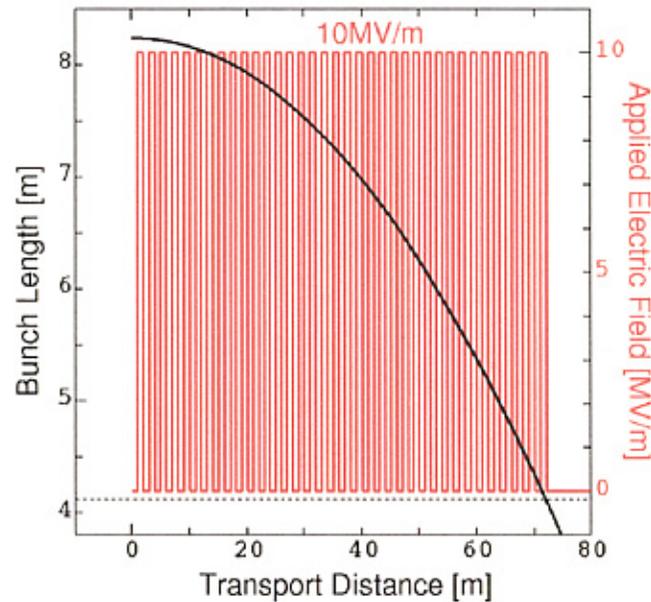
Estimated Buncher Parameters

Total Transport Distance	~ 45 km
Beam Rotation Time	~ 200 μ s
Induction Module Repetition	~ 3 MHz*
Unit Length	32 m
Buncher Circumference	64 m
Max Bunching Field	-700 ~ +700 kV/m*

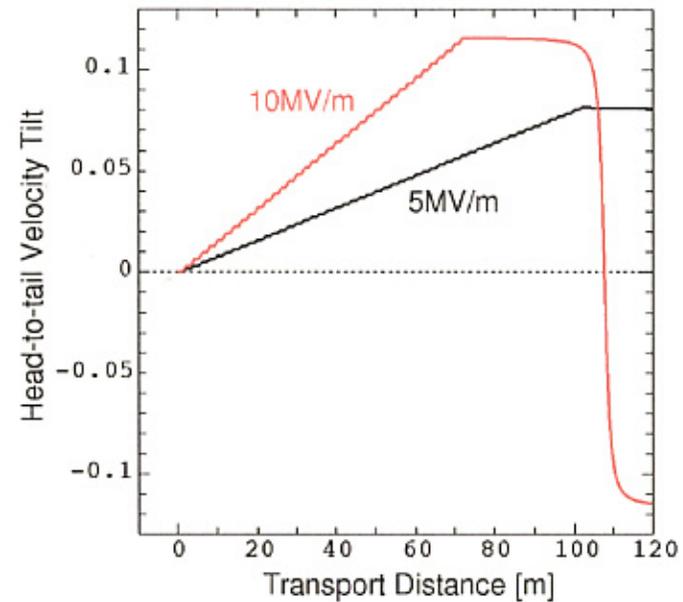
Although these are challenging parameters, *possible* by an extension of existing technology.

*K. Horioka, *et al.*, Proc. BEAMS2000, (2000), p.119.
M. Watanabe, *et al.*, Rev. Sci. Instrum. **73**, 1756 (2002).

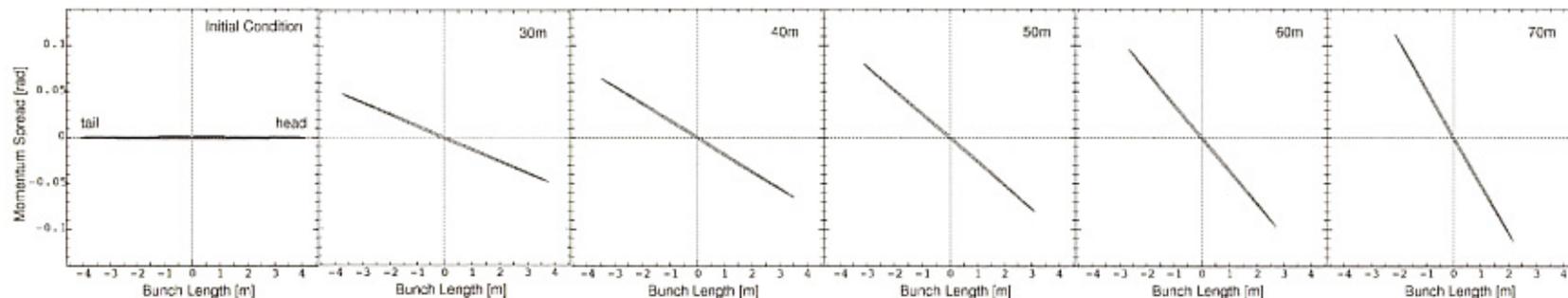
Beam Bunching using Induction Linac



Bunch length & applied electric field.
Bunching voltages are applied at each gap.



Velocity tilt variation during compression.
Velocity tilt is varied up to 10%!



Longitudinal Beam Envelope on Phase Space during Beam Compression

Bunching by $\Delta\beta/\beta$ & Bending without $\Delta\beta/\beta$



Compact Recirculating Beam Buncher with Quasi-Equilibrium Compression



Applied to Beam Buncher for RIKEN MUSES Project

Issues

● Repetitive Induction Modulator

● Target Physics

▶ Radiation hydrodynamics by
heavy ion beam irradiation

● Beam Physics

Focusing
Bunching
Bending
Dispersion ...