High-Current Beam Dynamics for HIF & HEDP Applications

Takashi Kikuchi

Utsunomiya University

with thanks to K.Horioka, M.Nakajima, T.Katayama, S.M. Lund, S.Kawata, T.Someya, J.Hasegawa, Y.Oguri, T.Sasaki, J.J. Barnard, D.P. Grote, M.Ogawa, A. Friedman, and many others

U.S.-Japan Workshop on Heavy Ion Fusion & High Energy Density Physics
"Academia Hall", Utsunomiya University, Sep. 28-30, 2005

Particle Beam for HIF & HEDP Applications

For HIF & Ion Beam Driven HEDP researches

➡ HED Plasma Generation by High Power Beam Irradiation

Power = Particle Energy x Beam Current

Large Particle Energy ➡ Broad Energy Deposition

➡ High Current Beam

⬇

Space-Charge-Dominated Beam Physics

Research Issues for HIF

HIF research issues are:

- High Flux ion source
- Acceleration and Transport of space charge dominated beam
- Bunch compression scheme at final stage of the accelerator
- Focusing and Irradiating on fuel pellet in reactor environment
- Energy Deposition process in target plasma
- Reactor System
- Energy Conversion

→ Study on space-charge-dominated beam in final beam bunching

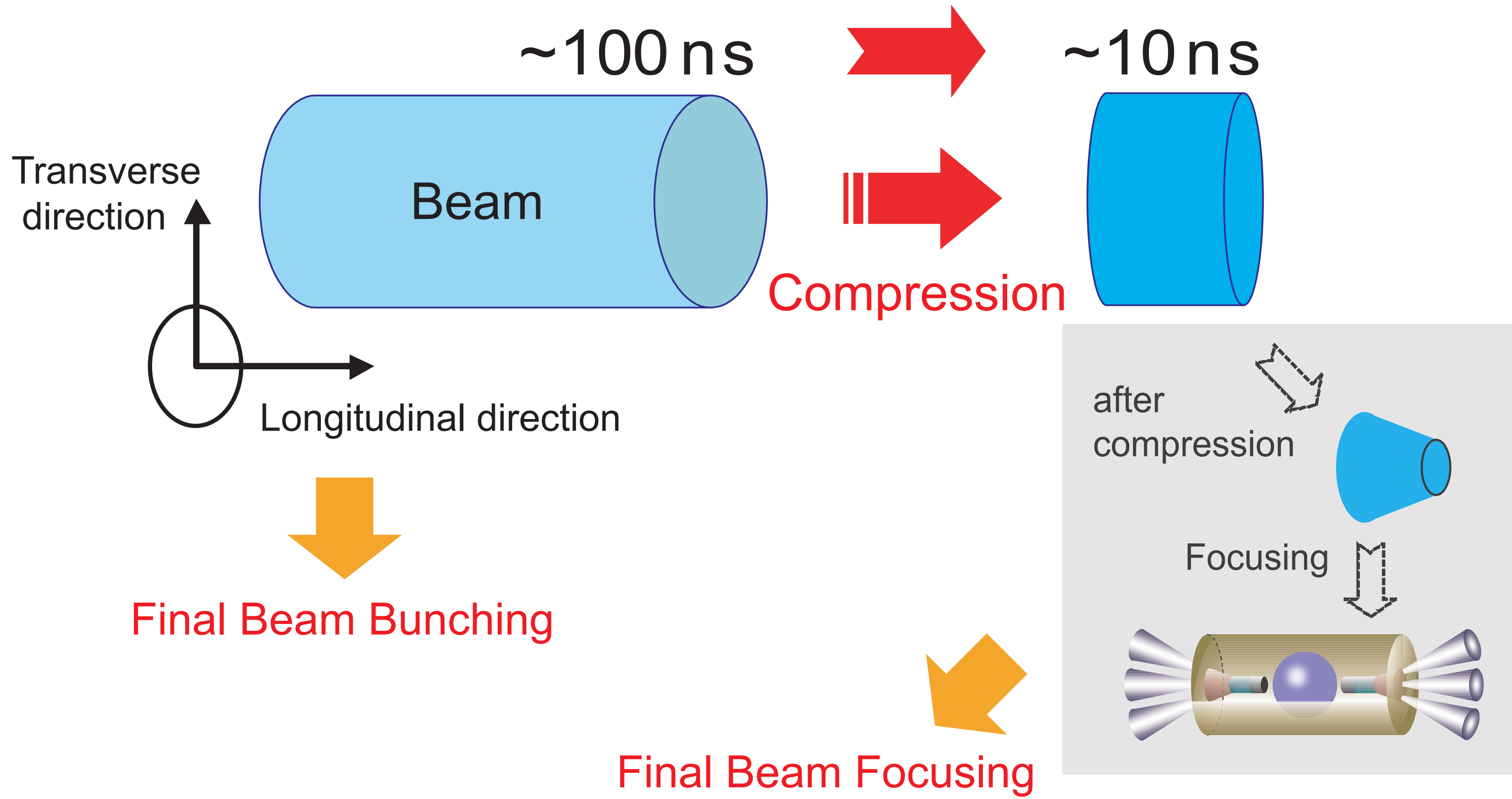
- Beam Dynamics
- Instability of Beam Transport
- Emittance Growth

Beam Instability & Dynamics induced by Space Charge Effect (Cooperative Phenomenon) are interested during Final Bunching.

Beam Bunching in Final Stage of HIF Driver

Intense Heavy Ion Beam (~10GeV ~10ns ~100kA) Generation & Transport are required for effective implosion.

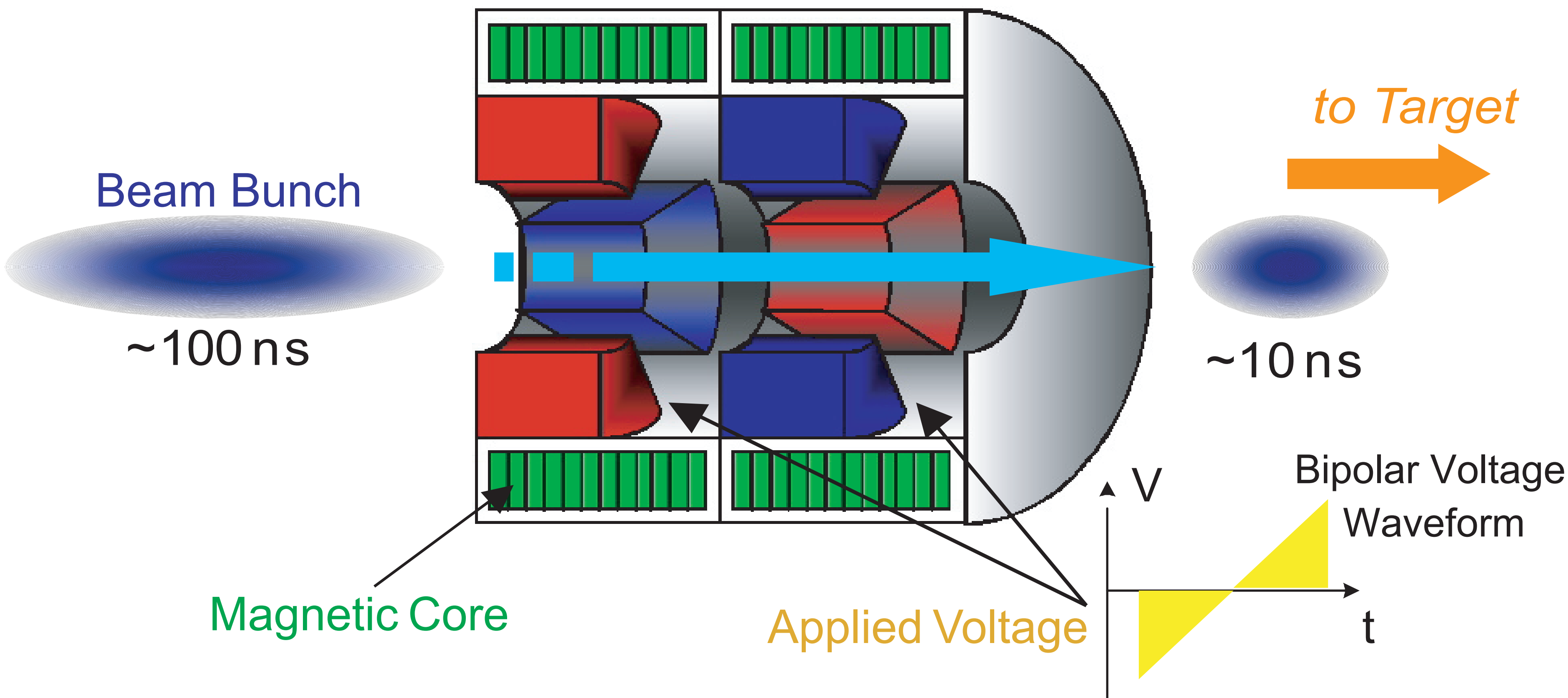
Accelerated beam must be longitudinally compressed in final stage of HIF driver.



Bunch Compression using Induction Modulator

One unit of induction beam buncher :

Induction buncher consists of periodic lattice,
gaps & FODO quadrupoles.



Head & tail velocities are modulated,

Beam head is decelerated
Beam tail is accelerated

Beam bunch becomes short during transport.

Beam Parameters

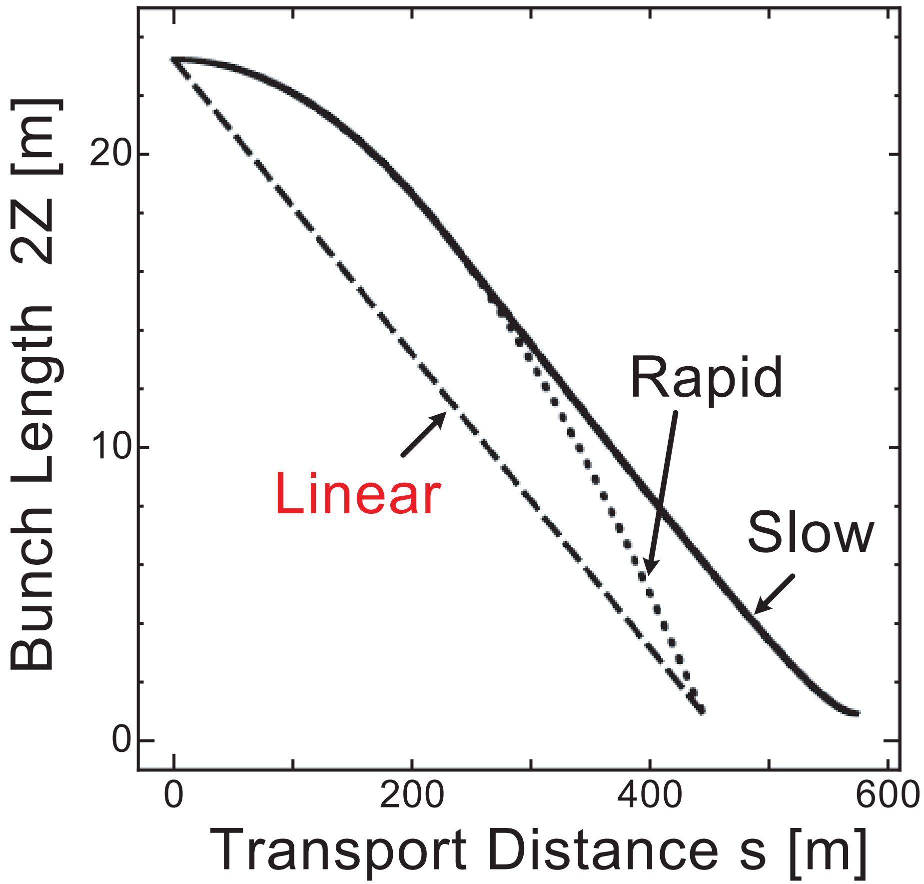
Ion Species	Pb^{1+} (207 amu)
Ion Number	2.5×10^{15}
Total Charge	0.4mC
Pulse Duration	250ns $\longrightarrow$ 10ns
Total Beam Current	1.6kA $\longrightarrow$ 40kA
Beam Number	4
Current per Beam	400A $\longrightarrow$ 10kA
Particle Energy	10GeV ($\beta \sim 0.31$)
Longitudinal Beam Length	23m $\longrightarrow$ 0.9m

Parameters in final stage of HIF driver system

Bunch Compression Ratio = 25 (= 250ns / 10ns)

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

Longitudinal Dynamics by Envelope Equation
(Neuffer Equation)



By Longitudinal Envelope Equation, bunch length is estimated during final beam bunching.

150S=450m (at least) for x25 Compression*

Simple Linear Compression Schedule is assumed as model for Longitudinal Bunch Dynamics.

*T. Kikuchi, M. Nakajima & K. Horioka, Laser Part. Beams 20, 589 (2002).

Calculation Model for Beam Dynamics during Final Bunching

- Transverse PIC simulation is carried out with longitudinal compression model (re-weighting*).

*S.M. Lund, *et al.*, Proc. PAC99, p.1785.

- Equation of Motion

$$\frac{d^2x_p}{ds^2} = -k_x x_p - \frac{q_p}{\gamma^3 m_0 v_z^2}\frac{\partial\phi}{\partial x}$$

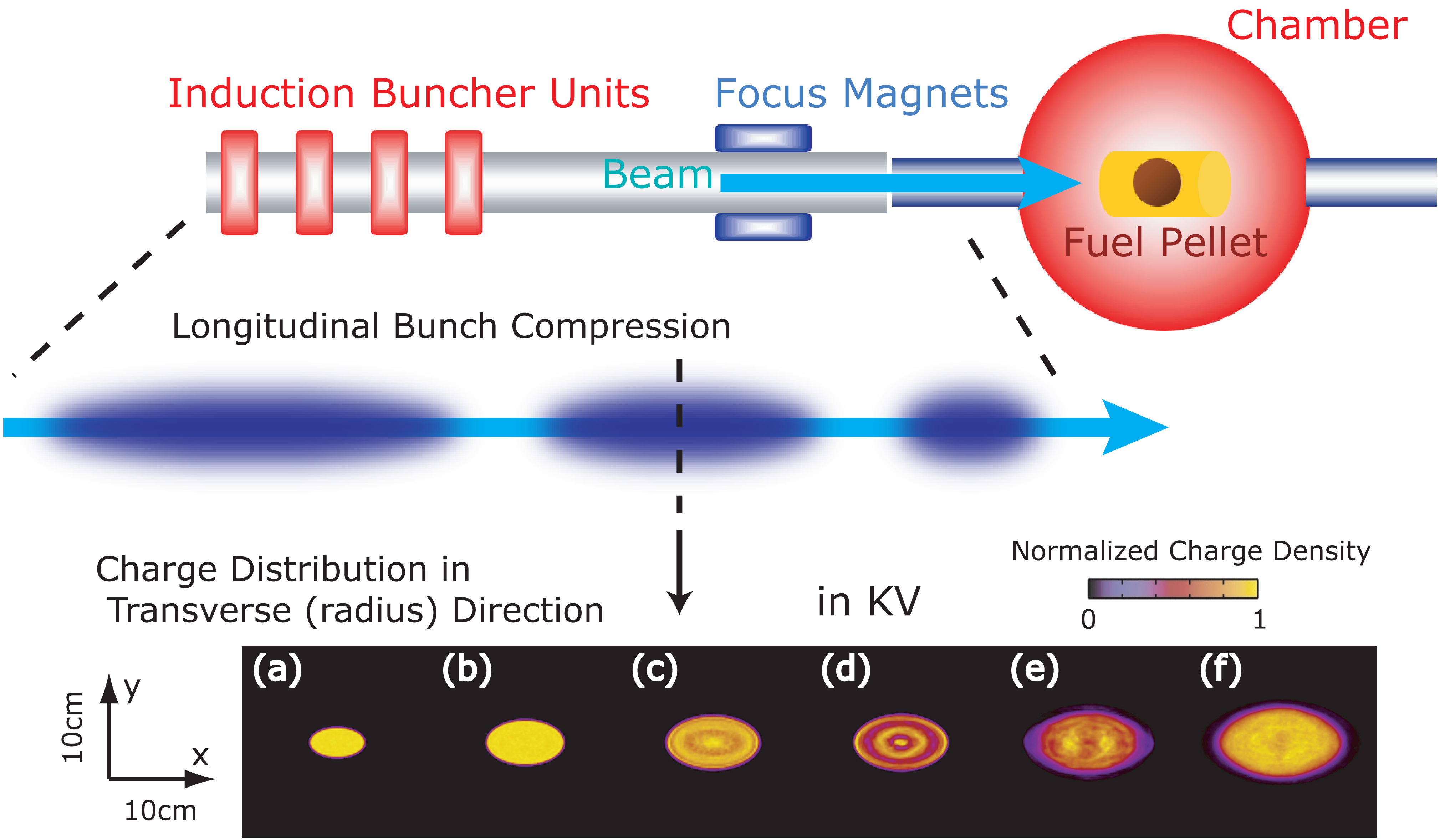
$$\frac{d^2y_p}{ds^2} = -k_y y_p - \frac{q_p}{\gamma^3 m_0 v_z^2}\frac{\partial\phi}{\partial y}$$

- Poisson Equation

$$\frac{\partial^2\phi}{\partial x^2} + \frac{\partial^2\phi}{\partial y^2} = -\frac{\rho}{\epsilon_0}$$

↓ Particle-in-cell (PIC) Method

Beam Dynamics during Final Beam Bunching



T. Kikuchi, M. Nakajima, K. Horioka, and T. Katayama,
Phys. Rev. ST Accel. Beams 7 (2004) 034201.

Growth of Flute Perturbation

Flute Perturbation Increase is considered as source of emittance growth.

Nonuniformity δn

Space Charge Potential

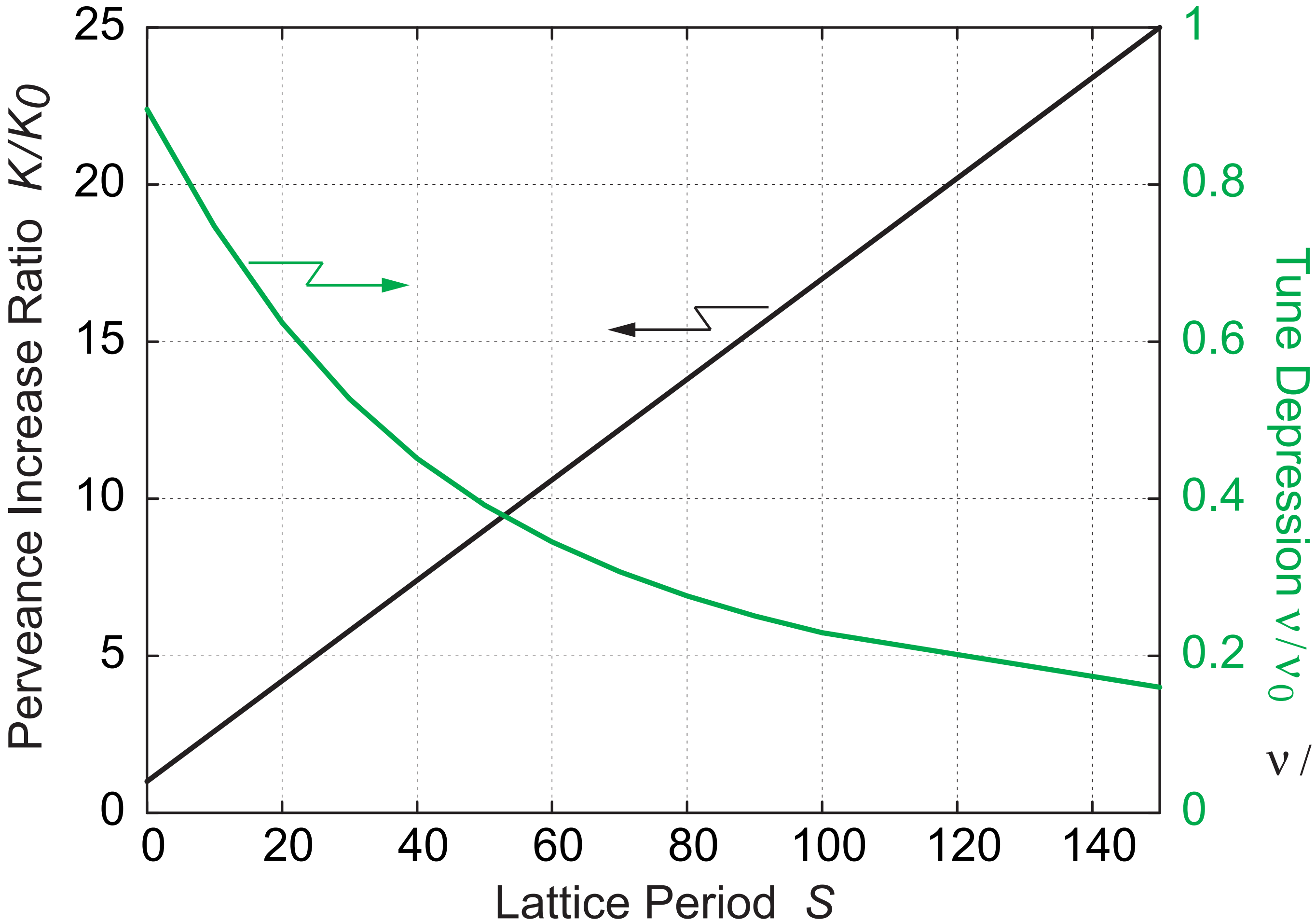
$$\phi = \underbrace{\phi_0(r)}_{\text{equilibrium}} + \underbrace{\delta\phi(r,\omega)\exp(-i\omega t)}_{\text{perturbation}}$$

Vlasov-Poisson Equations + KV Distribution

Dispersion Relation $(\omega^2)^m$

If Growth Rate $|\Im\,\omega| > 0$, Unstable

Estimation of Tune Depression during Bunch Compression



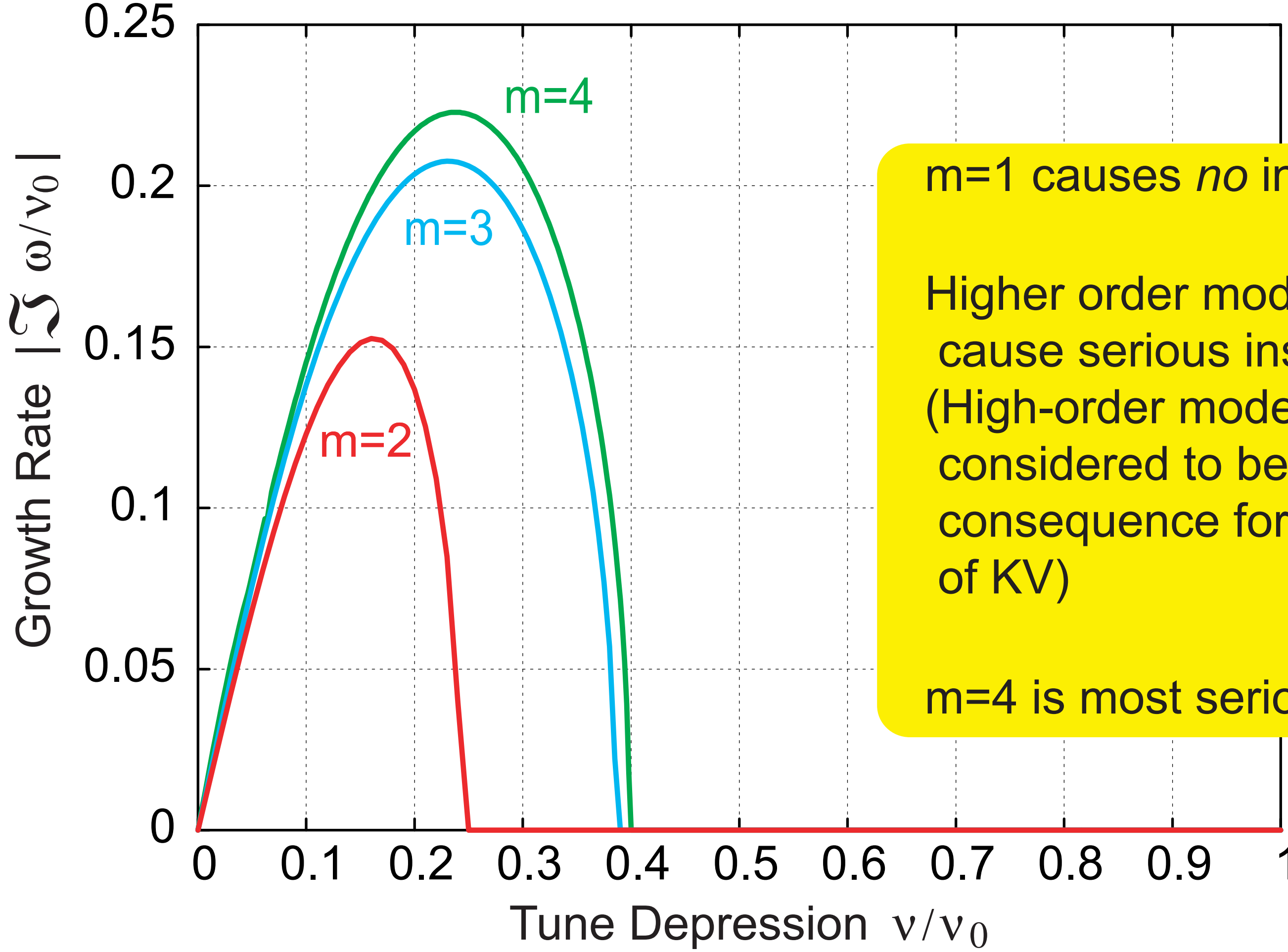
$$\alpha = \frac{K}{4\,\varepsilon_n \sqrt{k_t}}$$

$$\nu / \nu_0 = \sqrt{1 + \frac{\alpha^2}{4}} - \frac{\alpha}{2}$$

Tune depression is decreased with perveance (or current) increase.

It is predicted that growth of flute perturbation may be caused during final beam bunchig.

Growth Rate for each Mode of Axisymmetirc Flute Perturbation



m=1 causes *no* instability.

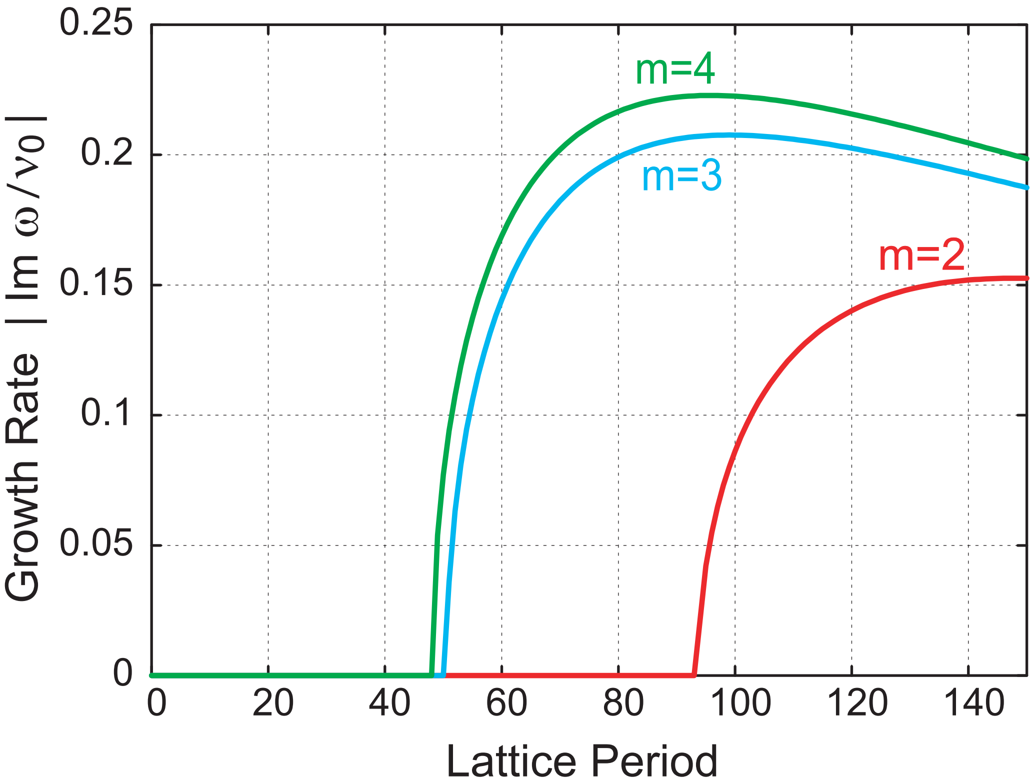
Higher order modes will not cause serious instability. (High-order modes are considered to be a consequence for singularity of KV)

m=4 is most serious.

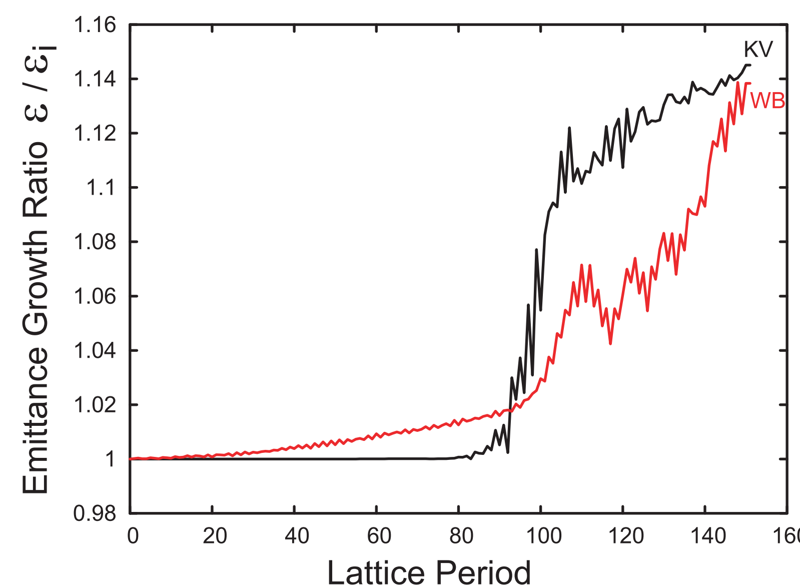
Axisymmetric flute perturbation will cause instability in region with low value of tune depression (region of strong space charge effect).

R.L. Gluckstern, *et al.*, Phys. Rev. E 54, 6788 (1996).
S.M. Lund & R.C. Davidson, Phys. Plasmas 5, 3028 (1998).

Growth Rate of Flute Perturbation during Bunching



Each mode of Axisymmetric Flute Perturbation grows during final beam bunching.



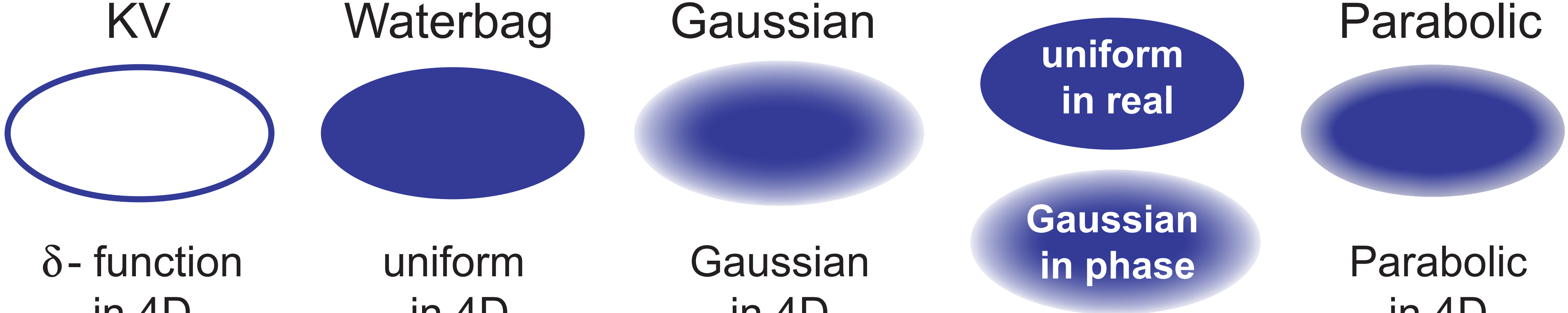
Regime of large growth rate corresponds to region of abrupt emittance growth given by PIC simulation.

T. Kikuchi, M. Nakajima, K. Horioka, T. Katayama, Phys. Rev. ST Accel. Beams 7 (2004) 034201.

Initial Particle Distribution *Images*

Five particle distributions are placed as initial condition:

KV | Waterbag | Gaussian | semi-Gaussian | Parabolic

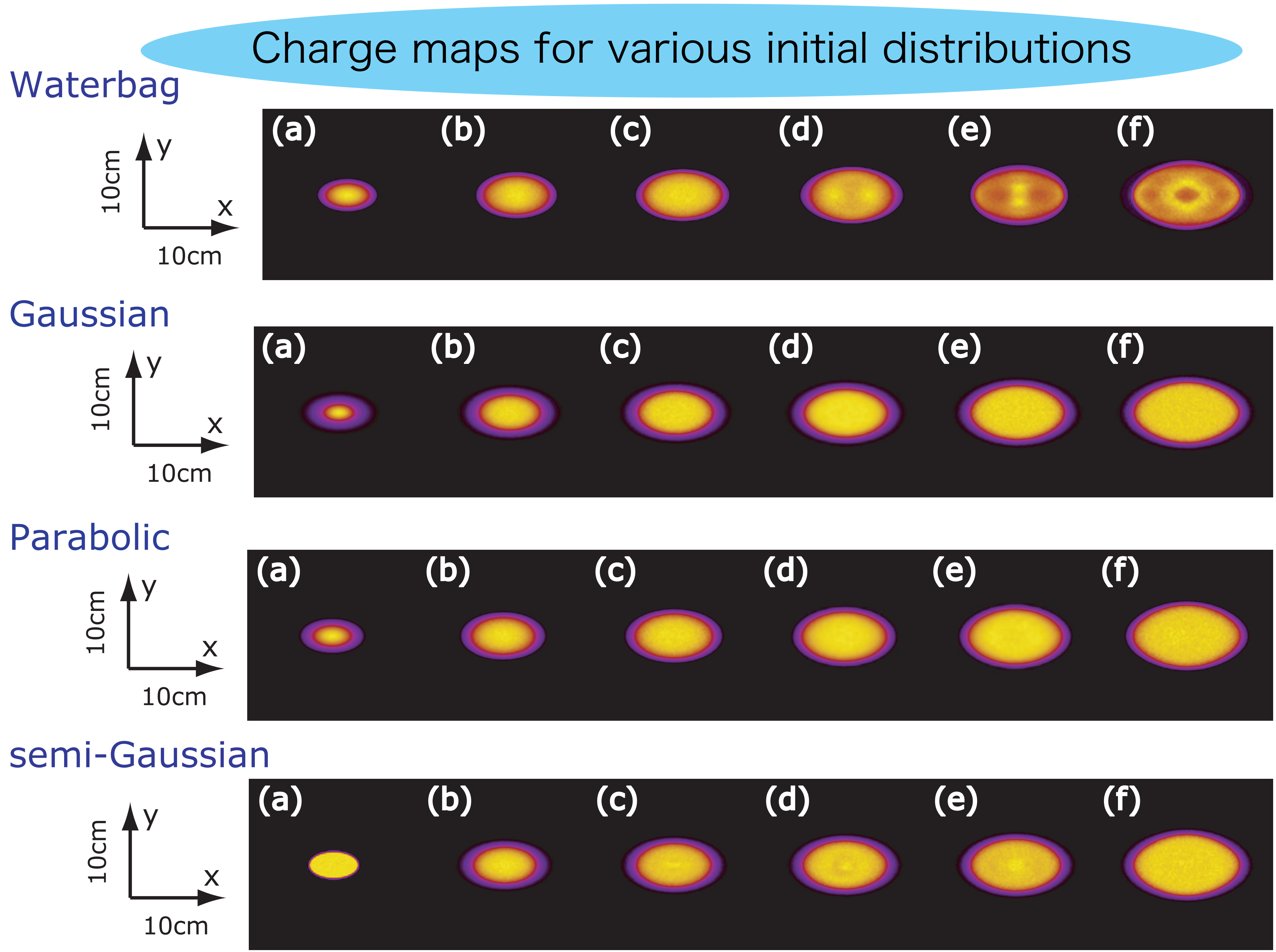


δ- function in 4D | uniform in 4D | Gaussian in 4D | Parabolic in 4D

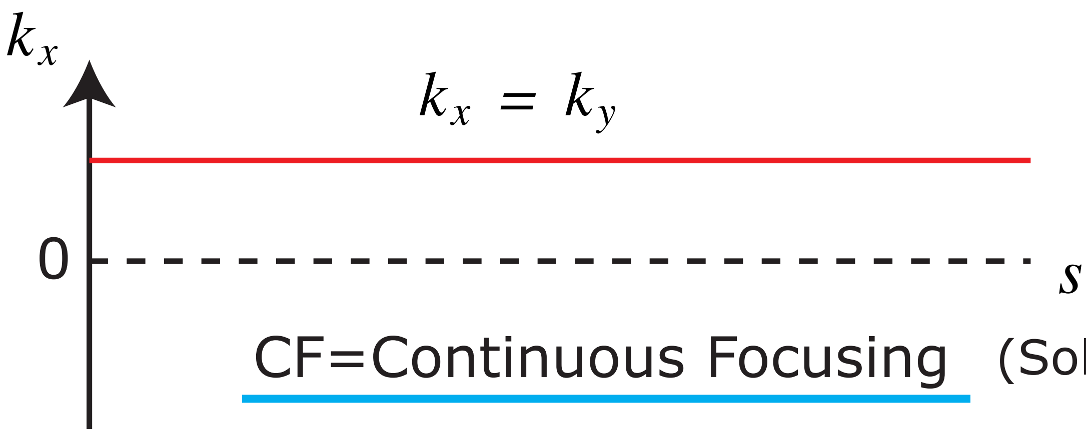
Note that the distributions are achieved in transverse 4D phase space!

f (x,y,x',y')

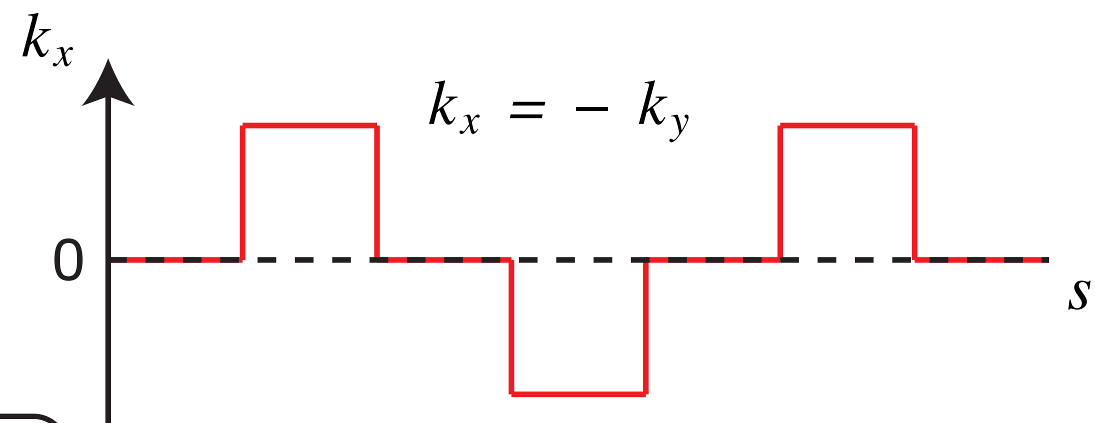
These are transversely distributed according to consideration of rms equivalent beam.


Charge maps for various initial distributions
Waterbag
Gaussian
Parabolic
semi-Gaussian
(a)
(b)
(c)
(d)
(e)
(f)
y
x
10cm
10cm

Transverse Focusing System



CF=Continuous Focusing (Solenoid)



AG=Alternating Gradient (FODO)

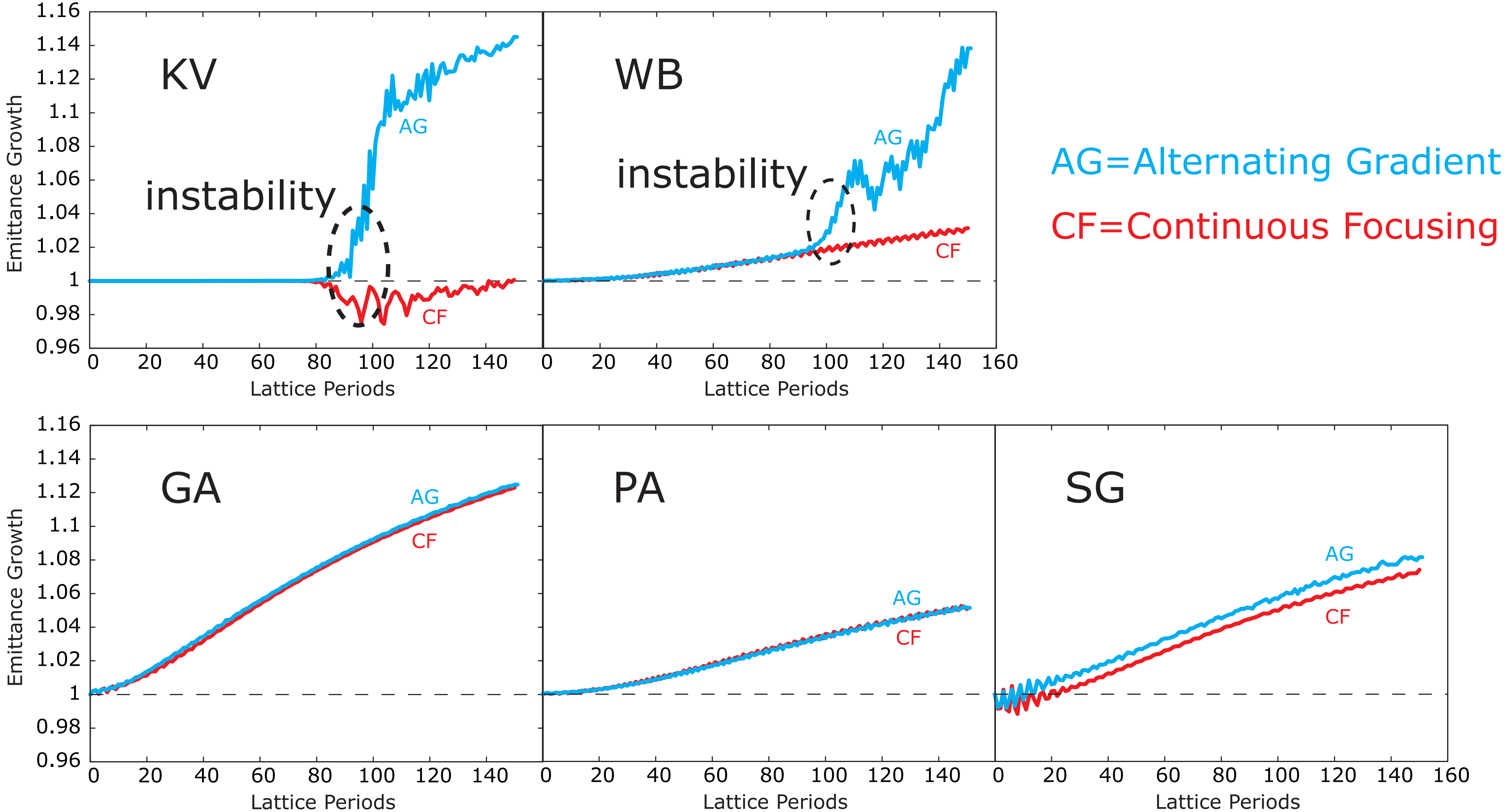
rms Transverse Emittances :

$$\varepsilon = (\varepsilon_{x,rms} + \varepsilon_{y,rms}) / 2$$

$$\varepsilon_{x,rms} = \left(\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle\right)^{1/2}$$

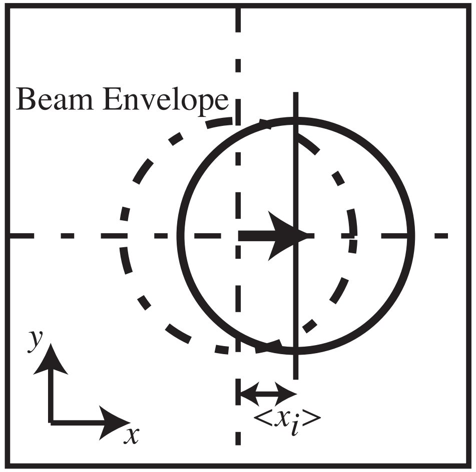
$$\varepsilon_{y,rms} = \left(\langle y^2\rangle\langle y'^2\rangle - \langle yy'\rangle\right)^{1/2}$$

Emittance Growth in Final Bunching with AG or CF Lattice



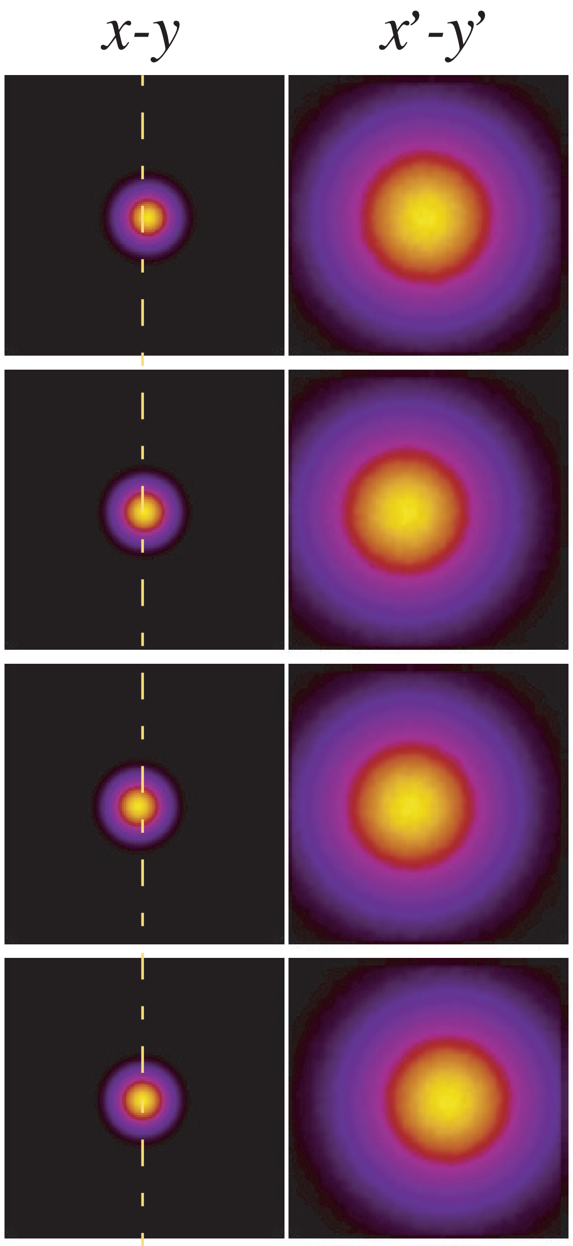
- For KV with AG & CF, beam instability is observed.
- For WB with AG, instability is caused, but can **not** appear for case with CF.
- Initial GA, PA, SG beams cause gradual emittance growth for cases with AG & CF.

Dipole Oscillation in Off-centered Beam



Off-centered beam model

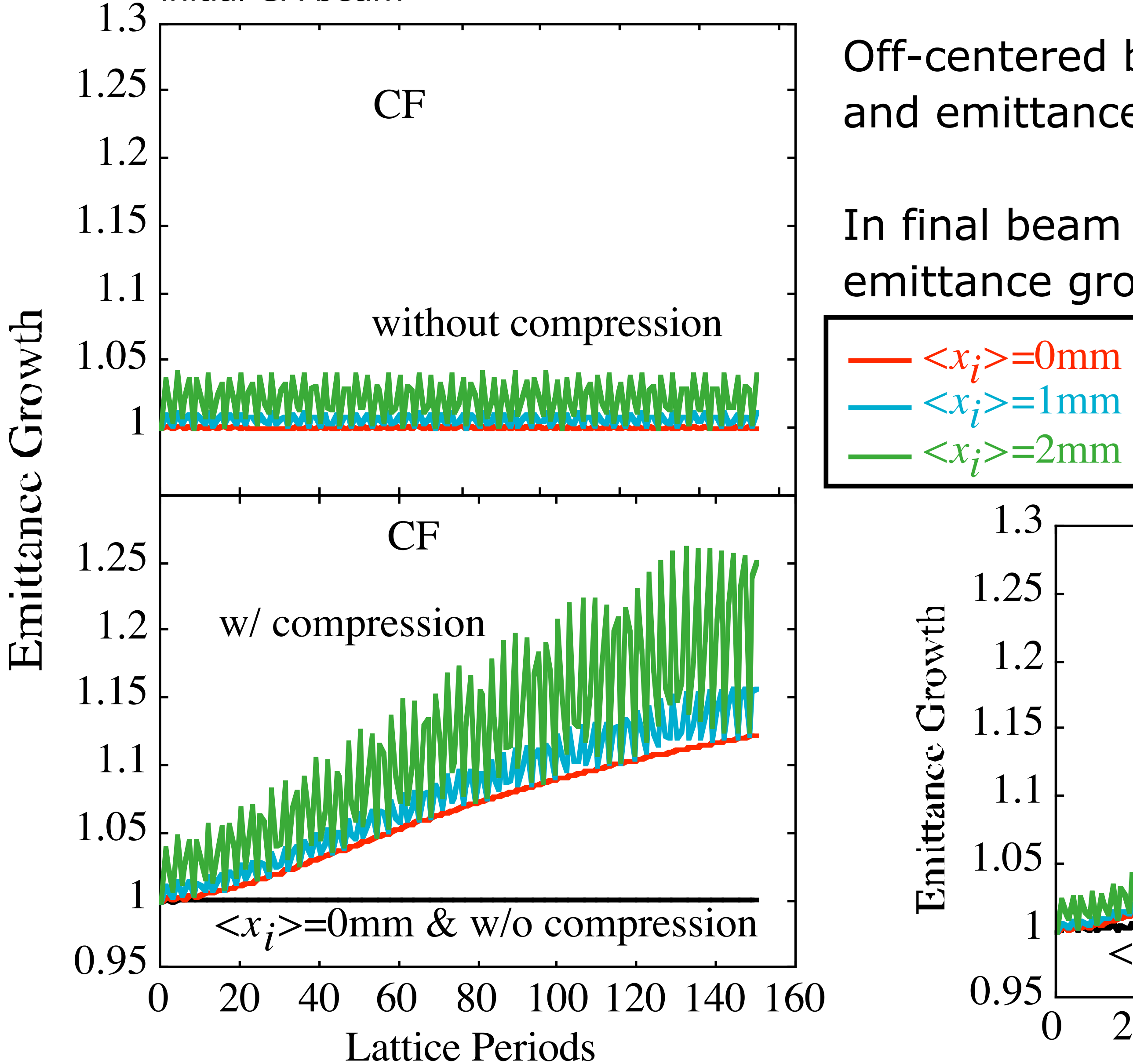
When center of beam is displaced (off-centered beam), beam oscillates during transport, because axis of transverse focusing force is given at $<x>=0$.



Simulation example in initial GA beam with CF at $\langle x_i \rangle=2$mm, for w/o compression

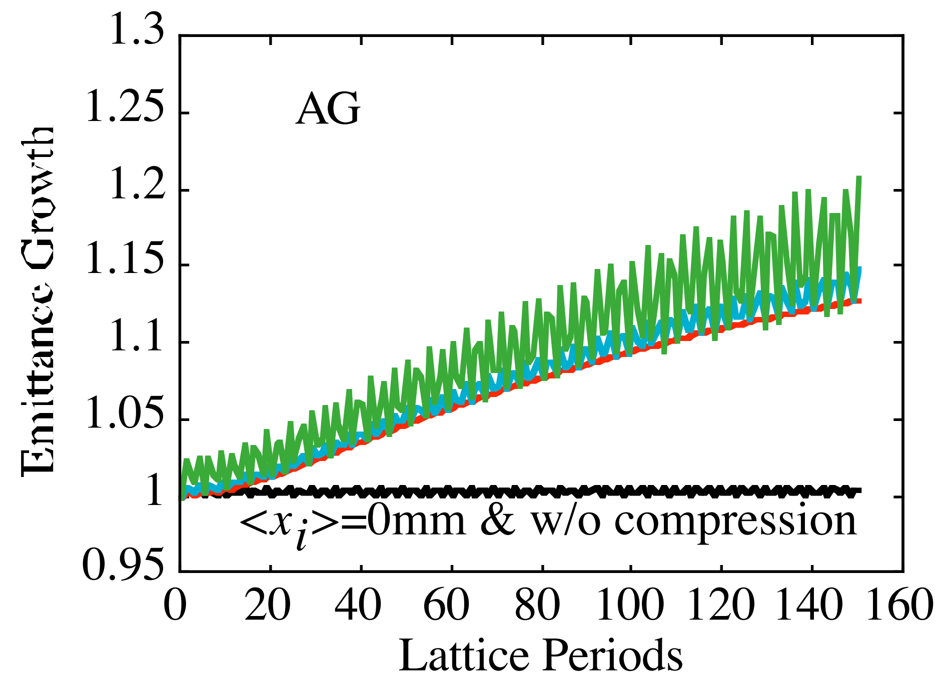
Emittance Growth with Dipole Oscillation

initial GA beam



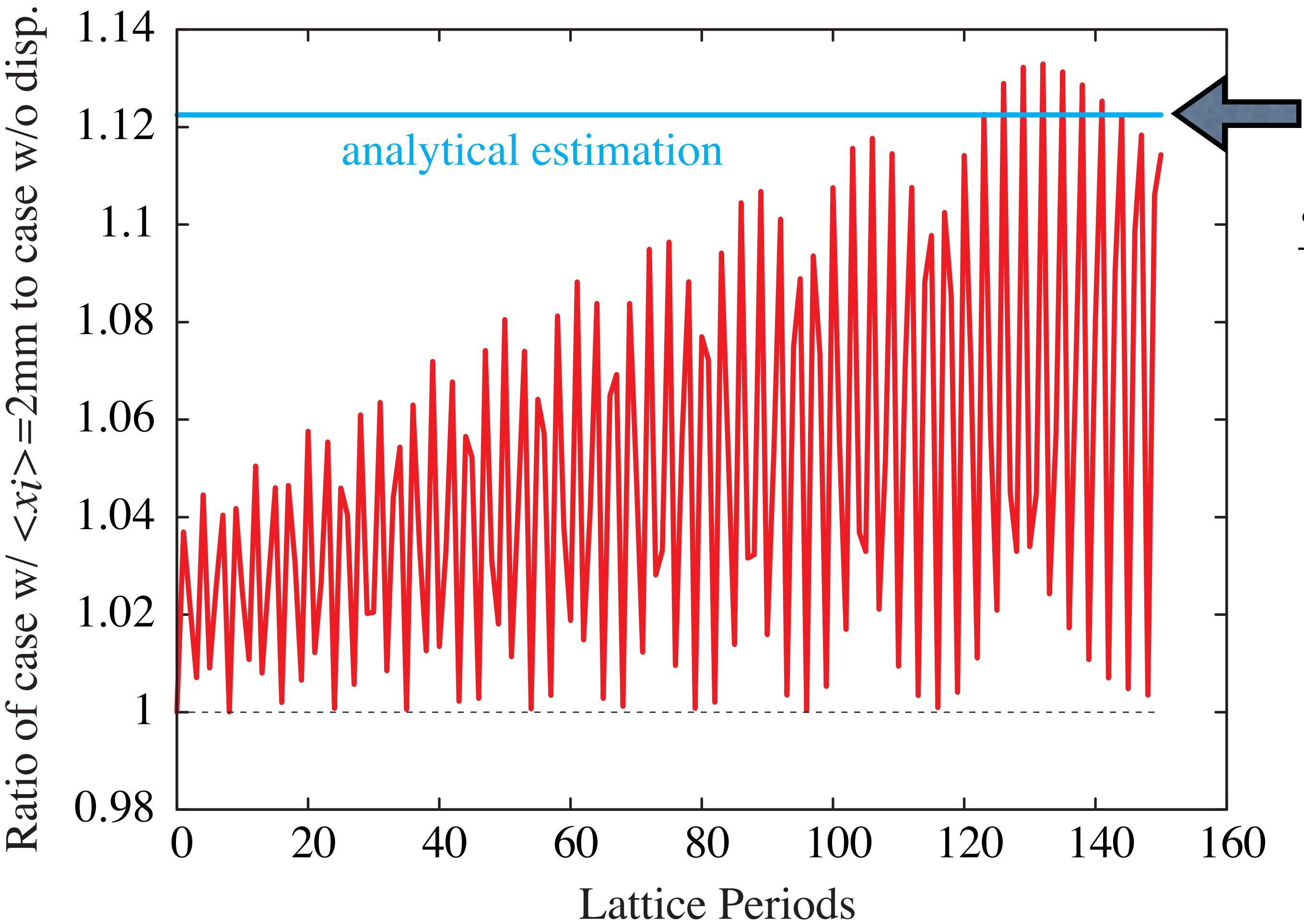
Off-centered beam causes dipole oscillation, and emittance also has oscillation.

In final beam bunching with displacement, emittance growth additionally increases.



Growth Ratio of cases w/ to w/o displacement

Estimation of Emittance Growth Rate due to Dipole Oscillation



$$\frac{\varepsilon_f}{\varepsilon_i} \approx \sqrt{1+\left(\frac{\sigma_0}{\sigma_i}\frac{\langle x_i \rangle}{X_i}\right)^2} \; *$$

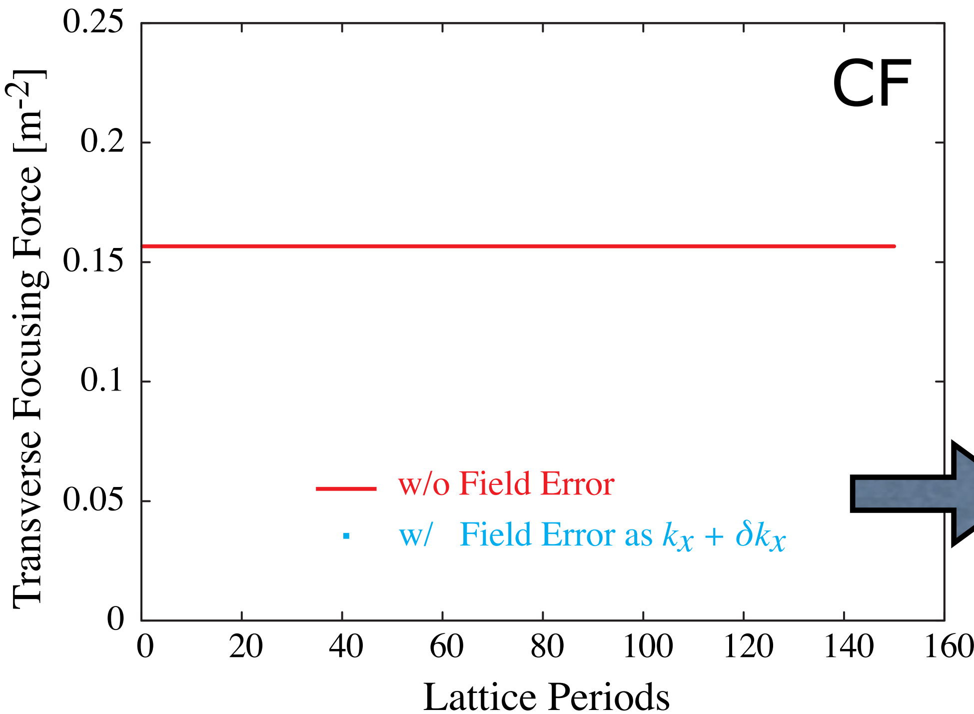
$$\left.\frac{\sigma_i}{\sigma_0}\right|_{L.P.=150} \approx 0.16$$

$$X_i \approx \frac{\varepsilon_t S}{\sin \sigma_i}$$

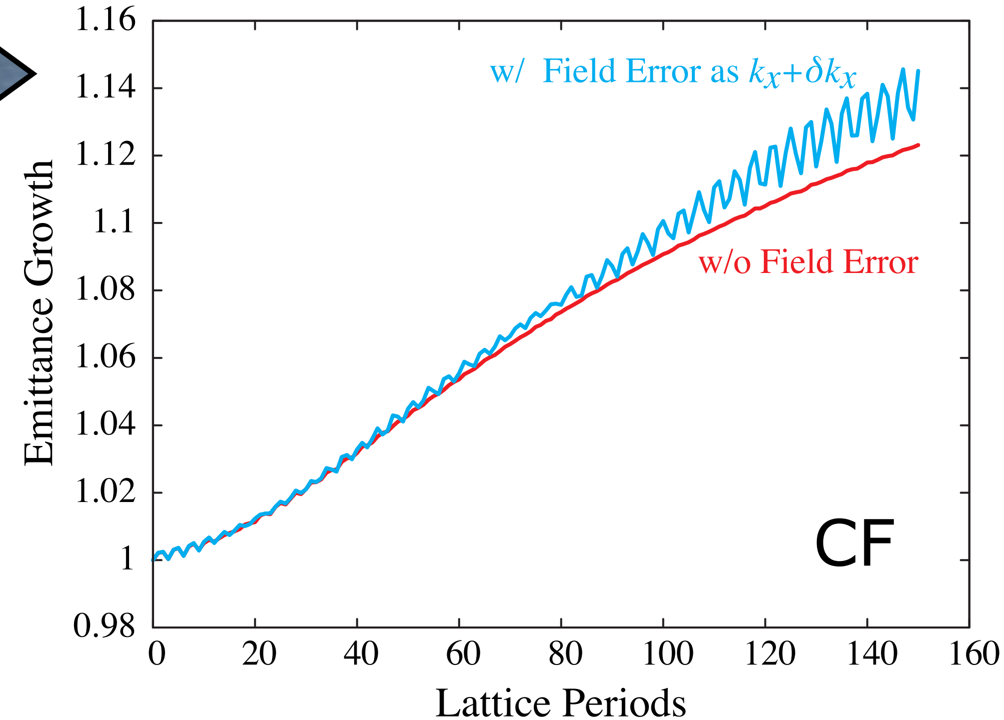
* M.Reiser, *Theory and Design of Charged Particle Beams*, Wiley, New York, (1994).

Influence of Focusing Field Error

Transverse focusing field error -> Emittance Growth



Additional emittance growth after compression



field error $\left(\frac{\delta k_x}{k_x}\right)_{\mathrm{r.m.s}} = 0.1$

only 2% difference

Summary

- Emittance growth during bunch compression was observed.
- Beam instability is one of sources of emittance growth at KV & WB beams with AG lattice.
- Initial GA, PA & SG beams cause gradual emittance growth for cases with CF & AG lattice.
- Emittance growth increases additionally by bunch compression with center displacement.