Transport Window for Bunching Beams in a Final Stage of Heavy Ion Inertial Fusion

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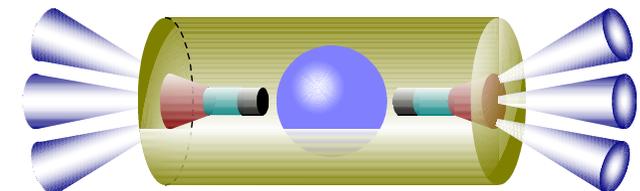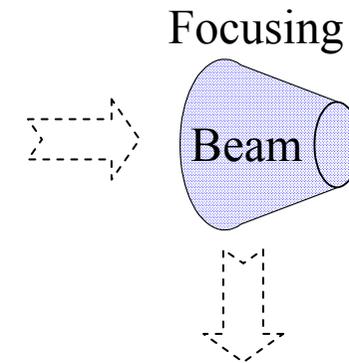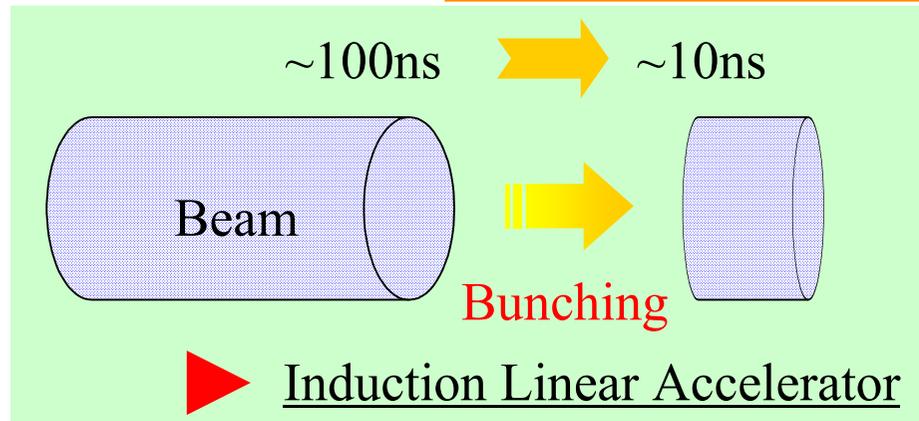
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● **Heavy Ion Inertial Fusion**

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

Accelerated Heavy Ion Beam ▶ Final Beam Bunching

~100ns ⇨ ~10ns

Focusing
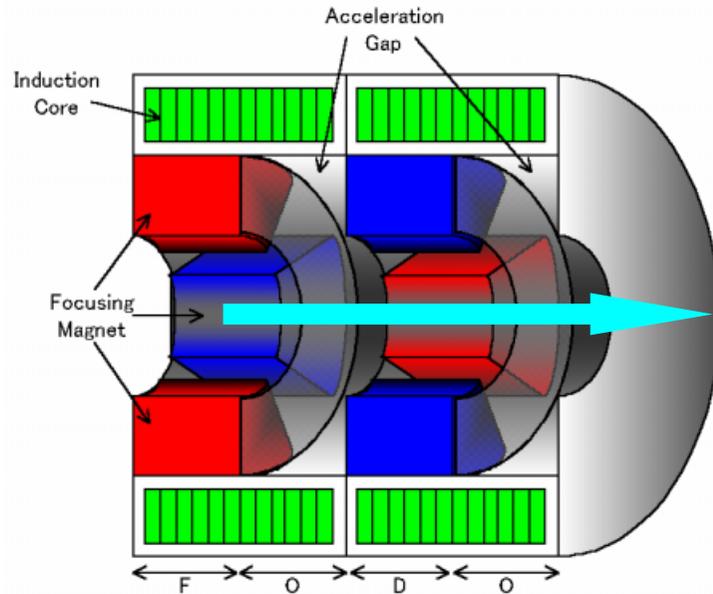
Beam ⇨

Bunching

Beam

▶ Induction Linear Accelerator

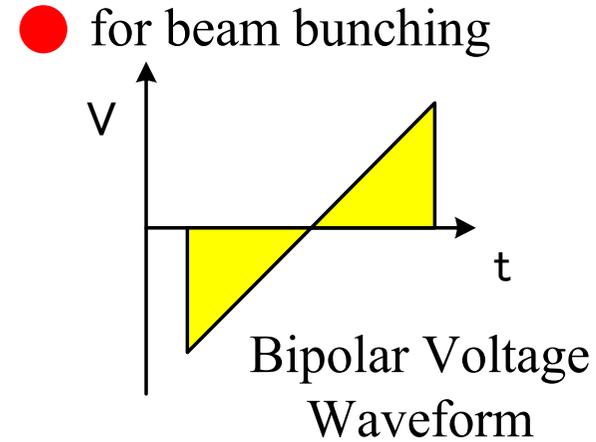Beam Irradiation for Implosion

Researches:

● Dynamics of Bunching Beam

● **Bunching Beam Transportability in Phase Advancing Condition**

Heavy Ion Beam Bunching by Induction LINAC

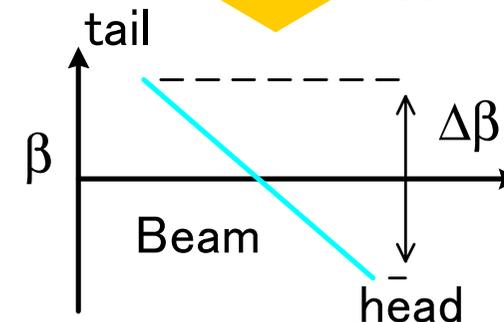Apply Bunching Voltage at each Gap

for beam bunching

Bipolar Voltage Waveform

apply to beam

Induction buncher consists of periodic lattice, acceleration gaps & FODO quadrupole.

Head & tail velocities are modulated.
$\Delta\beta/\beta$ indicates Velocity Tilt.

Beam head is decelerated
Beam tail is accelerated
by

Beam bunch becomes short during transport.

Velocity Tilt Induced Instability

Head-to-Tail Velocity Tilt for Bunch Compression

▶ Transverse Mismatch in terms of Quadrupole Lens

● Envelope Oscillation
● Resonance Instability

⬇

Beam Transport Instability

Prediction ▶ Resonance Effect by Phase Advance Modulation

↳ Verify Simple Estimation of Instability
using Particle-Core Model

Beam Parameters

|	
Ion Species	Pb^{1+} (207.2 amu)
Ion Number	2.5×10^{15}
Total Charge	0.4mC
Pulse Duration	250ns $\Rightarrow$ 10ns
Total Beam Current	1.6kA $\Rightarrow$ 40kA
Beam Number	4
Current per Beam	400A $\Rightarrow$ 10kA
Particle Energy	10GeV ($\beta \sim 0.31$)
Longitudinal Beam Length	23m $\Rightarrow$ 0.9m

Parameters in final stage of HIF driver system

Bunch Compression Ratio = 25

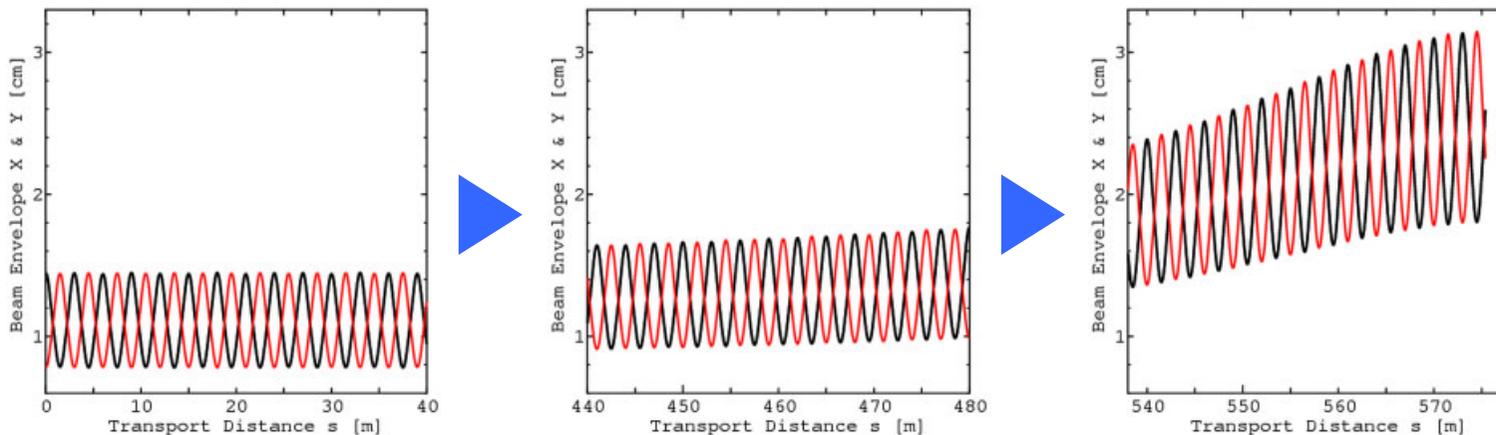by J.J. Barnard, *et al.*, Physics of Fluid B **5**, 2698 (1993).

Envelope Calculation Result with Bunching

▶ Longitudinal Behavior
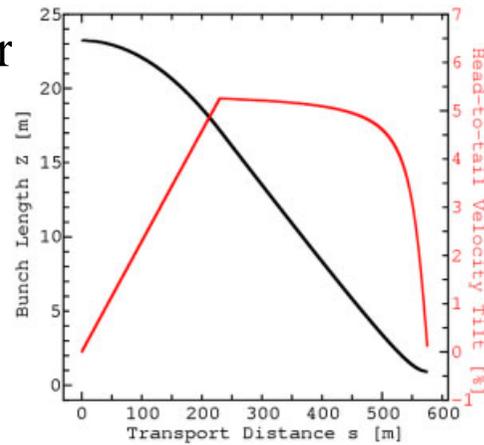
Bunching voltages apply
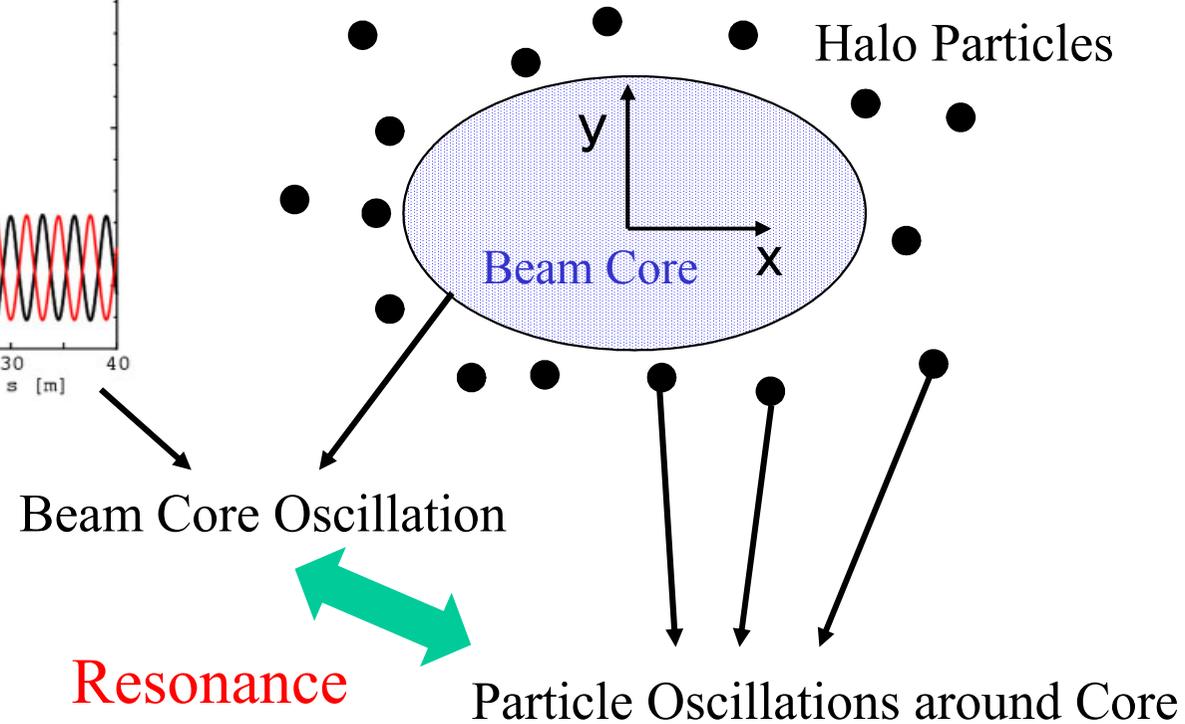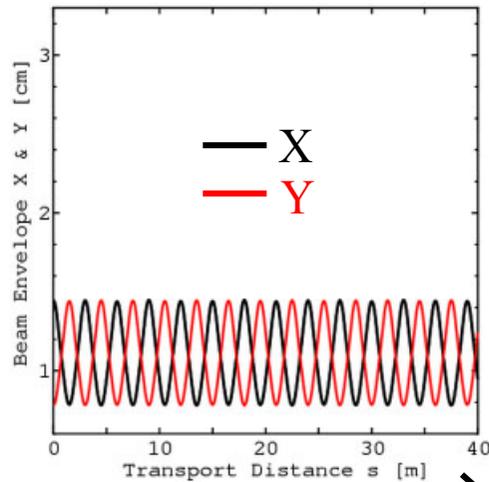velocity tilt to beam,
bunch compression is caused.

▶ Transverse Behavior

Beam bunching causes current (perveance) increase.
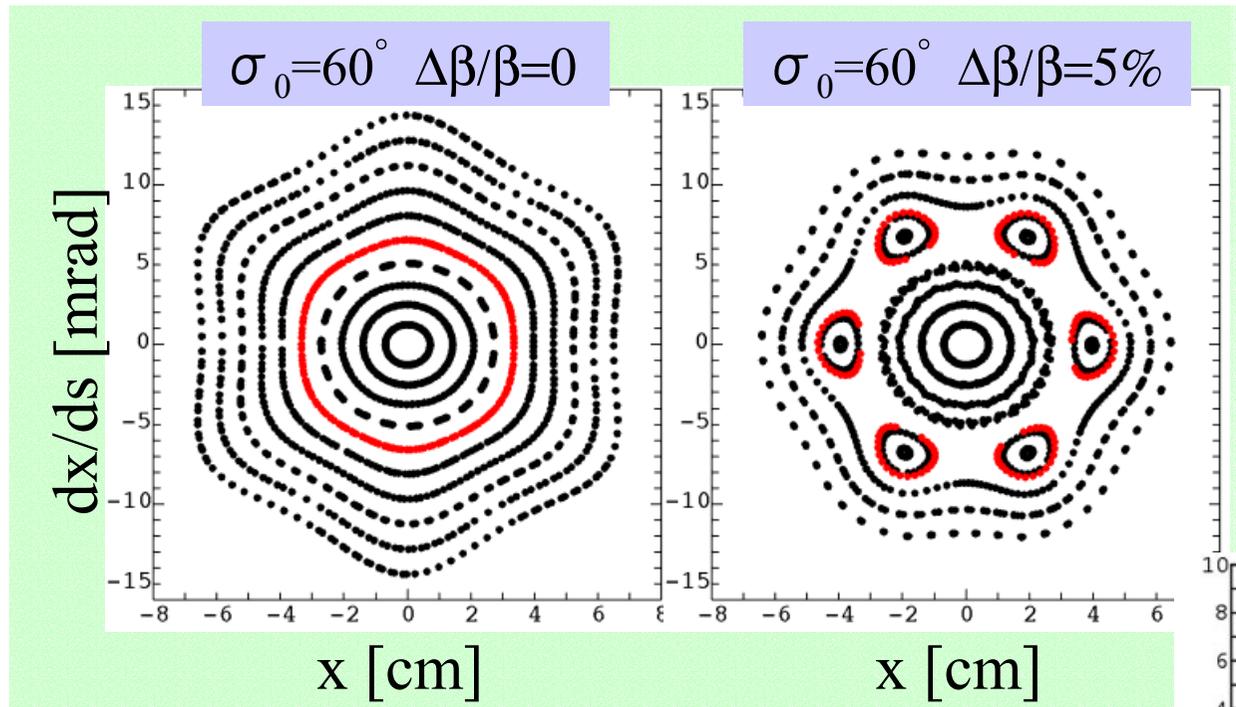
➡ Radius Expansion

Core/Particle Resonance

Halo Particles

Beam Core

Beam Core Oscillation

Particle Oscillations around Core

Resonance
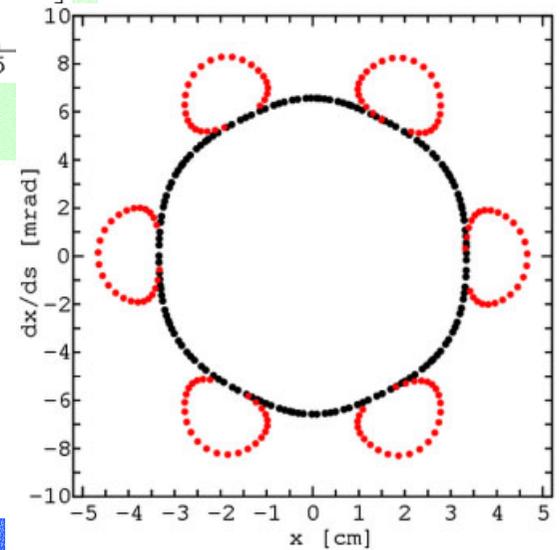
$$\omega_{core} / \omega_{particle} = integer$$

Halo formation, larger orbit of particle, chaotic behavior, etc. are induced by resonance.

by J.-M. Lagniel, *Nucl. Instrum. Methods Phys. Res.* **A345** (1994) 46.

Poincaré Maps

$\sigma_0 = 60° \quad \Delta\beta/\beta = 0$

$\sigma_0 = 60° \quad \Delta\beta/\beta = 5\%$
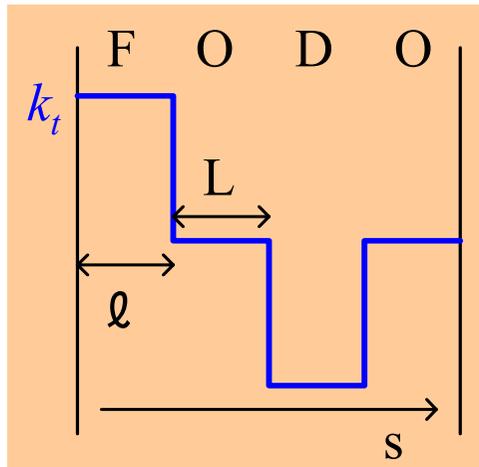

dx/ds [mrad]

x [cm]

x [cm]

Lager Orbit
by Resonance

**Resonance reentrance
due to $\Delta\beta/\beta$**

Particle Loss & Halo Formation

Expression of Phase Advance in FODO Lattice

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from Transfer Matrix

$$\cos \sigma_0 = \cos\theta\cosh\theta + \frac{L}{\ell}\theta(\cos\theta\sinh\theta - \sin\theta\cosh\theta) - \frac{1}{2}\left(\frac{L}{\ell}\right)^2\theta^2\sin\theta\sinh\theta$$

σ_o : Phase Advance without Space Charge [deg]
θ : Focusing Strength of Lens [rad]
L : Length of Drift Space (O in FODO) [m]
ℓ : Length of Focusing Space (F or D in FODO)

$$k = \left(\frac{\theta}{\ell}\right)^2$$

➡ Calculate σ_0

σ : Phase Advance Depressed by Space Charge

$$\cos\sigma = \cos\sigma_0 + 2K\left(\frac{\ell+L}{\bar{a}}\right)^2$$

$$\bar{a}^2 = \frac{2\varepsilon_t(\ell+L)}{\sin\sigma}$$

Average Beam Radius

➡ Estimate σ

Beam Envelope Calculation

$$X \equiv X(s) \qquad Y \equiv Y(s) \qquad Z \equiv Z(s) \qquad s : \text{Transport Distance}$$

Transverse Envelope Equation (K-V Distribution)

$$\frac{d^2 X}{ds^2} = -\tilde{k}_t X + \frac{2\tilde{K}}{X+Y} + \frac{\varepsilon_t^2}{X^3}$$

$$\frac{d^2 Y}{ds^2} = \tilde{k}_t Y + \frac{2\tilde{K}}{X+Y} + \frac{\varepsilon_t^2}{Y^3}$$

$$\tilde{k}_t \propto \frac{1}{\tilde{\beta}\,\tilde{\gamma}}$$

$$\tilde{K} \propto \frac{1}{\tilde{\beta}^2\,\tilde{\gamma}^3}$$

modulated by Δβ/β

k_t : Transverse Focusing Force
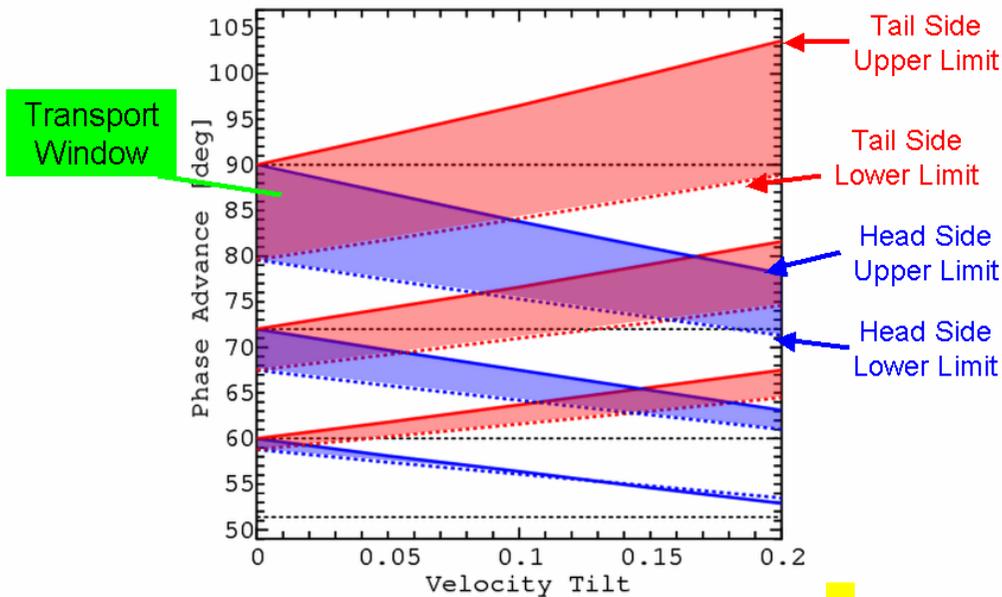K : Transverse Perveance

Longitudinal Envelope Equation

$$\frac{d^2 Z}{ds^2} = -k_z + \frac{K_L}{Z^2} + \frac{\varepsilon_{zz'}^2}{Z^3} = 0$$

k_z : Longitudinal Focusing Force
K_L : Longitudinal Perveance

Velocity Tilt induces Beam Envelope Mismatch

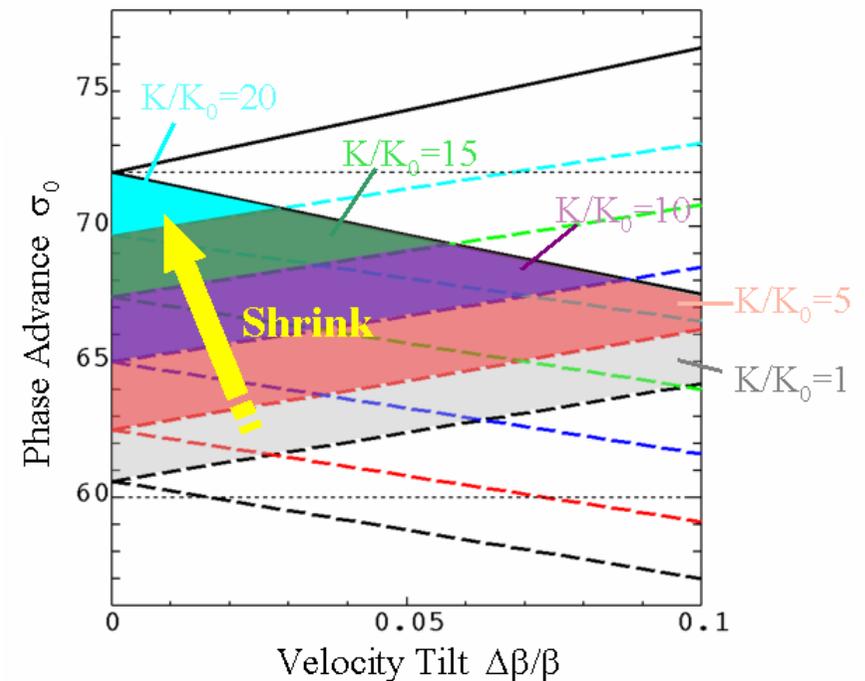# Transport Window Shrinking with Compression

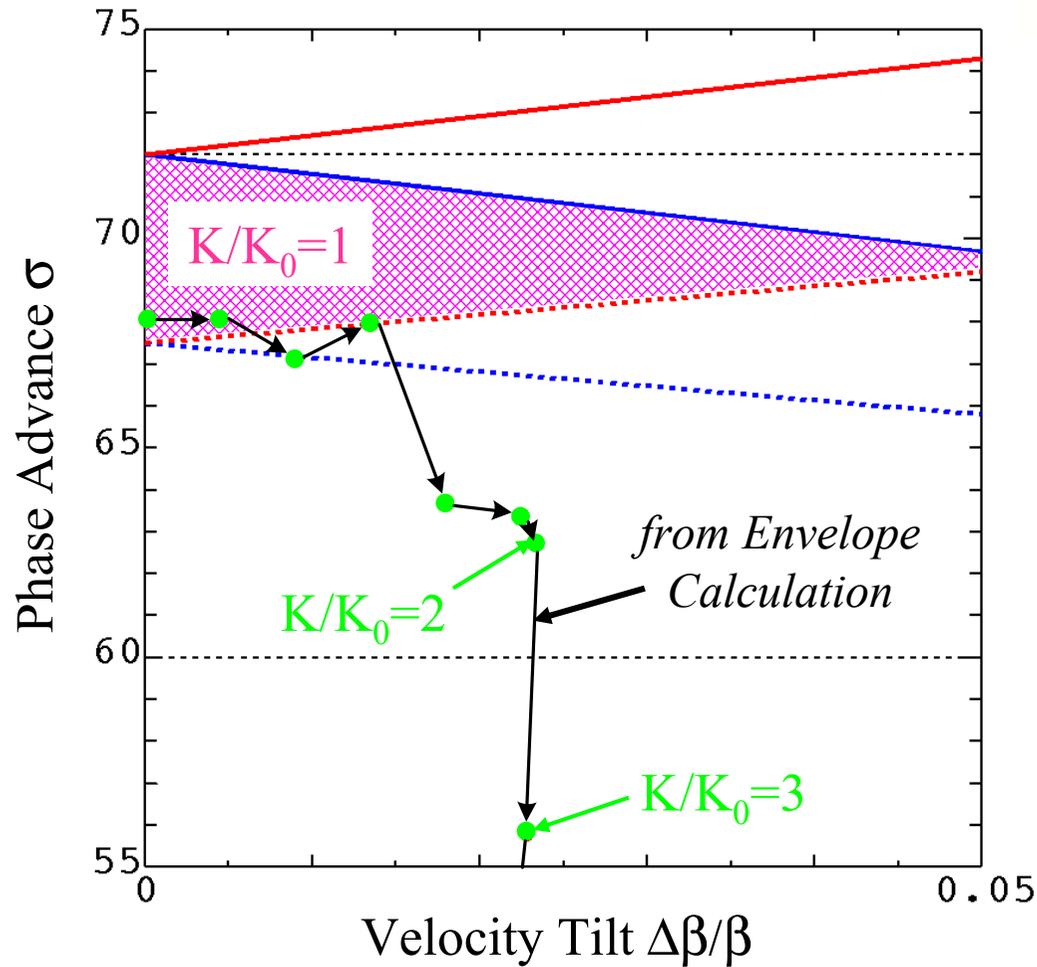Tokyo Institute of Technology

For Avoiding the Resonance Conditions ...

Transport Window becomes small with longitudinal compression (K increase).

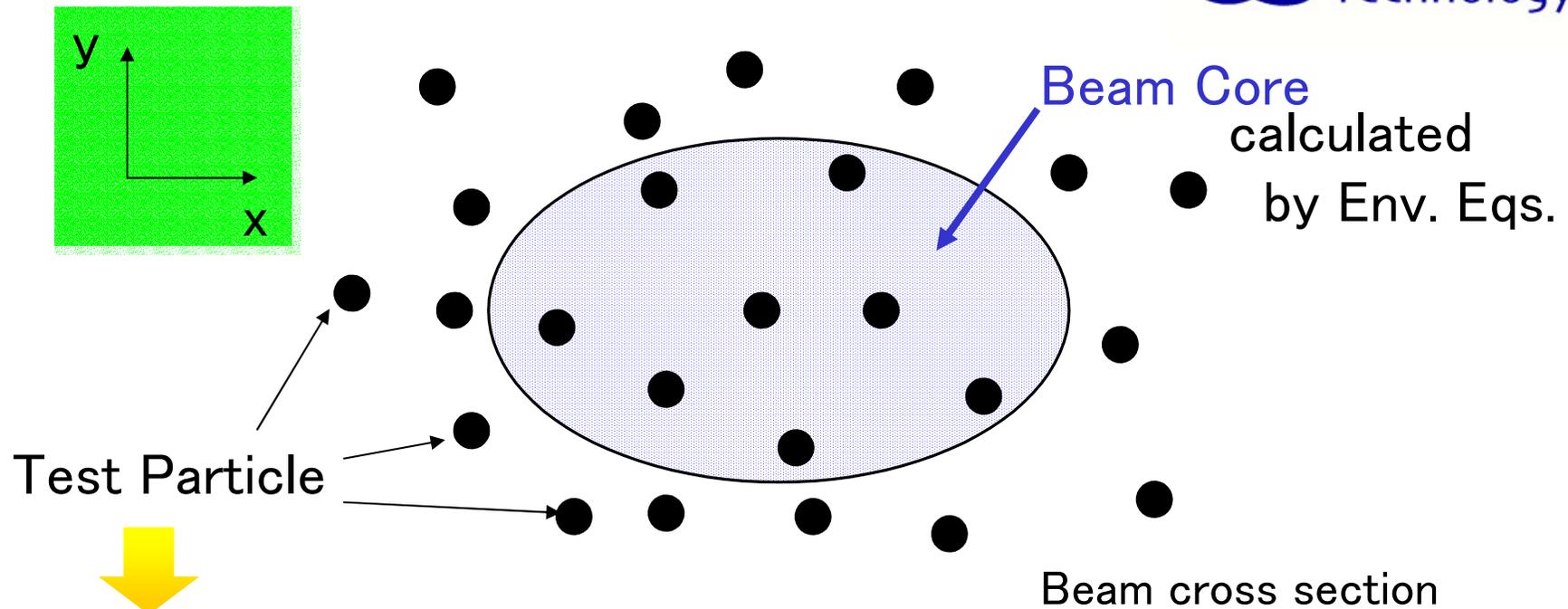It is difficult that entire beam stability is maintained during compression.

Phase Advance Dynamics with Compression

at Z/3

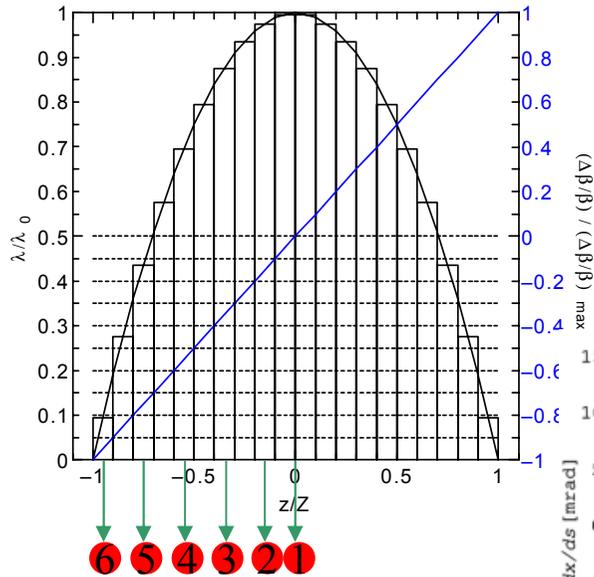▶ The phase advance goes off Transport Window during compression.
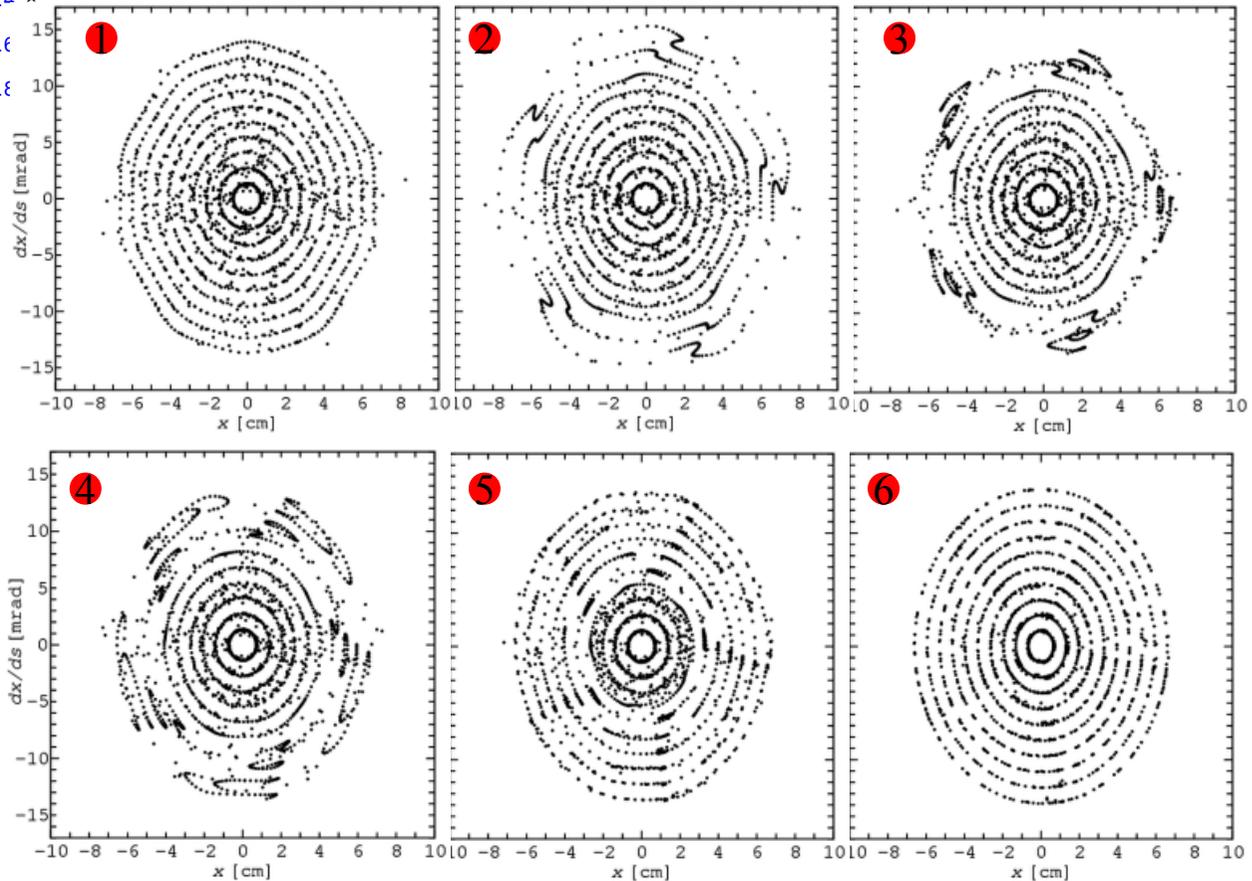
Particle-Core Model (PCM) Calculation

Beam Core

calculated by Env. Eqs.

Test Particle

Beam cross section

Test Particle Equation in PCM

$$\frac{d^2 x}{ds^2} = -\widetilde{k}_x x + \begin{cases} \dfrac{2\widetilde{K}}{X(X+Y)}x & \left(|x| \le X\right) \\[4mm] \dfrac{\mathrm{sgn}(x)\cdot 2\widetilde{K}}{|x|+\sqrt{x^2+Y^2-X^2}} & \left(|x| > X\right) \end{cases}$$

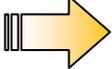# Poincaré plot at each slice with compression

PCM calculations are carried out at each sliced position.
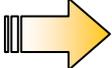Each Poincaré plot is shown in

From relation between velocity tilt & perveance, resonance effect is appeared at near center, rather than beam head.
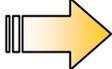
Summary

➡ Resonance reentrance due to $\Delta\beta/\beta$

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Instability Growth

➡ Simple Prediction of Phase Advance Modulation

Resonance Reentrance & Envelope Mismatch

➡ decide Transport Window for Bunching Beam

Transport Window changes with Longitudinal Compression