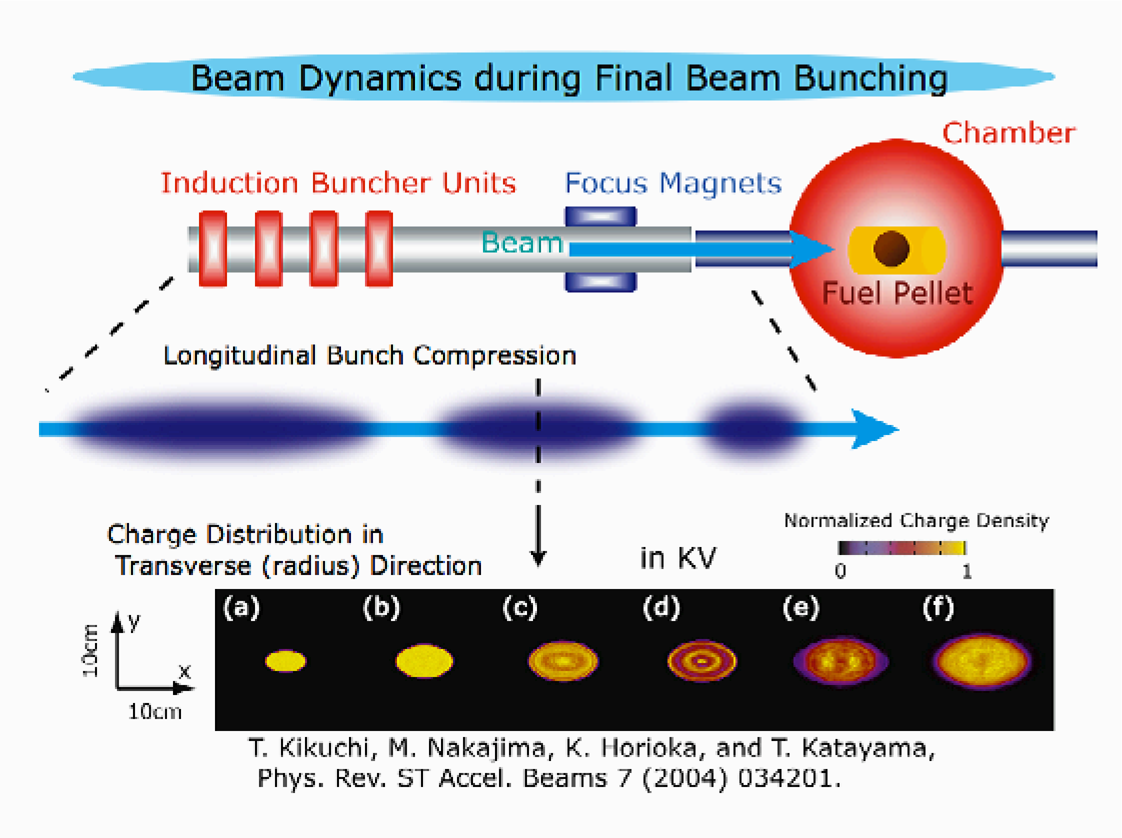
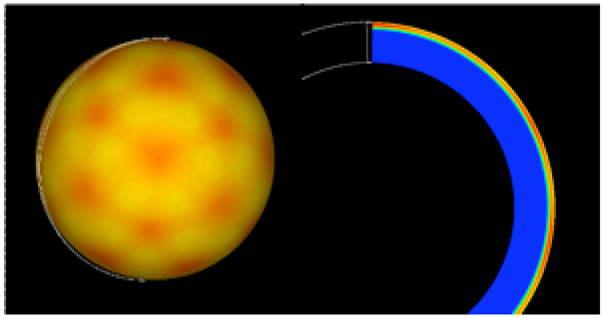
HIF Direct-Drive Targets / R-T Instability

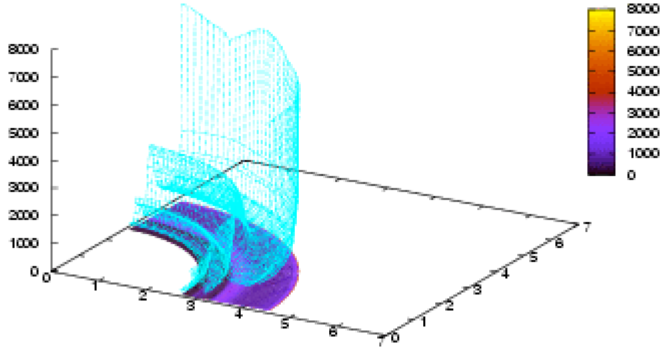
S. Kawata, T. Kikuchi
Utsunomiya University

1) Beam Physics _ Final Beam Bunching
2) HIF Implosion & Robust HIB illumination
3) Rayleigh-Taylor Instability Study in HEDP

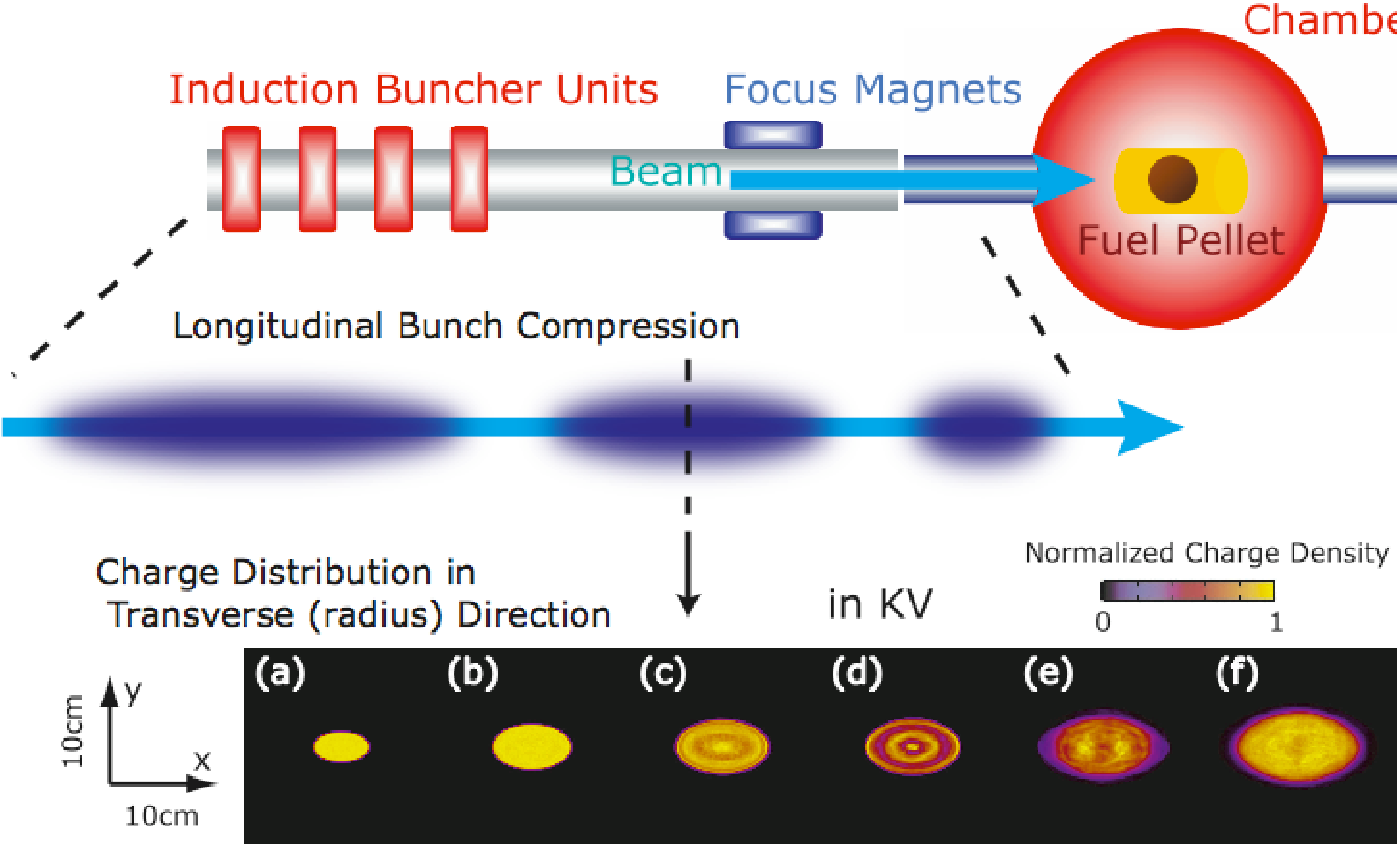


T. Kikuchi, M. Nakajima, K. Horioka, and T. Katayama, Phys. Rev. ST Accel. Beams 7 (2004) 034201.





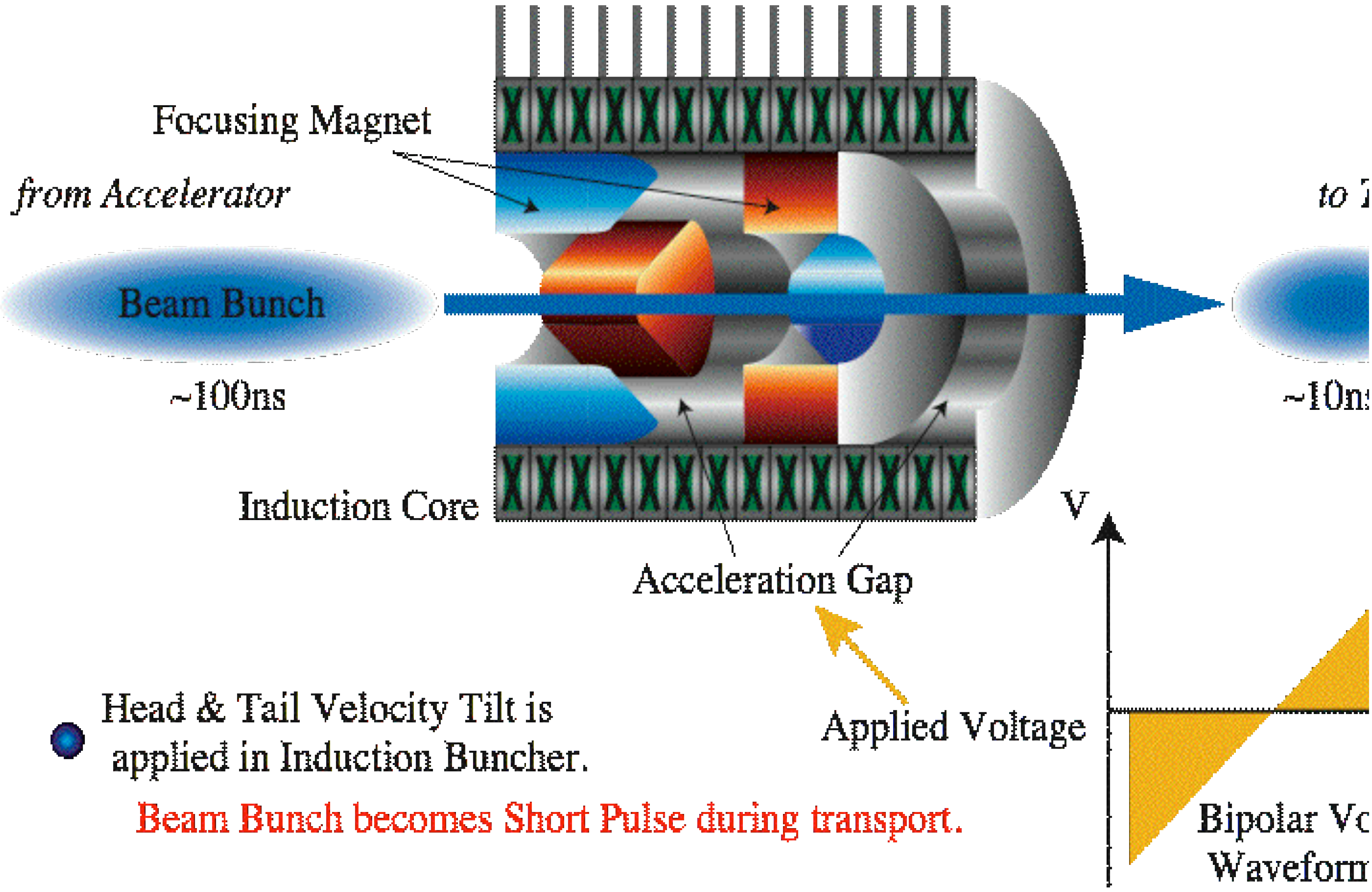
Beam Dynamics during Final Beam Bunching



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

Bunch Compression using Induction Modulator

Induction buncher consists of periodic lattice



- Head & Tail Velocity Tilt is applied in Induction Buncher.

Beam Bunch becomes Short Pulse during transport.

3D Beam Particle Dynamics

- Longitudinal - Transverse Coupling Motions
- Effect of Longitudinal Velocity Dispersion
  Limitation of Head-to-Tail Velocity Tilt
- Pulse Shape Deformation due to
  Space-Charge Wave

Develop 3D Particle Code

but, full 3D calculation is hard work...

Code Descriptions

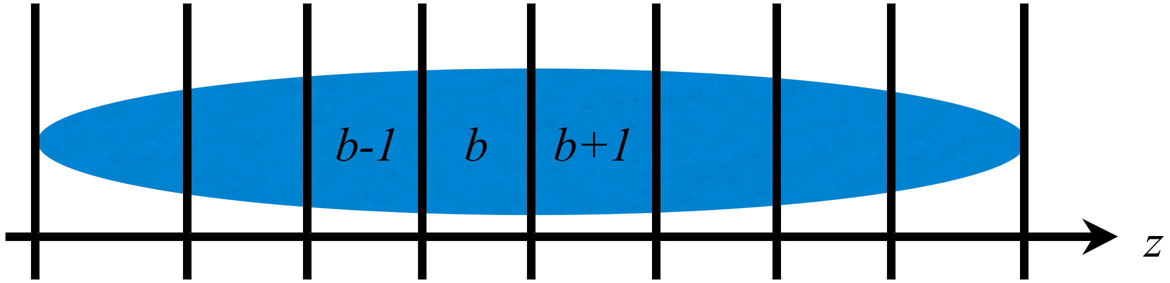
- Electric Fields

Longitudinal Electric Field = Long Wave Approximation

$$E_z = -\frac{g}{4\pi\epsilon_0{\gamma_0}^2}\frac{d\lambda}{dz},$$

$$g \sim \log\frac{r_p^2}{r_x r_y},$$

Transverse Electric Field = Poisson Eq.



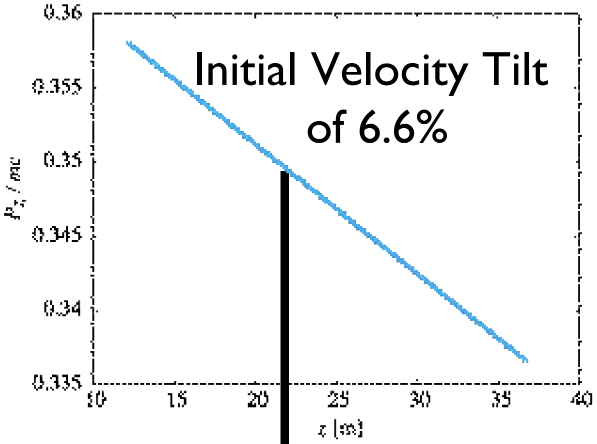
$$\frac{dE_{zb}}{dz} = -\frac{1}{4\pi\epsilon_0{\gamma_0}^2}\frac{d}{dz}\left(g_b\frac{d\lambda_b}{dz}\right),$$

$$\frac{\partial^2\phi_b}{\partial x^2} + \frac{\partial^2\phi_b}{\partial y^2} = -\rho_b', \qquad \rho_b' = \frac{\rho_b}{\epsilon_0} - \frac{\partial E_{zb}}{\partial z},$$

- Particle Motions

x, y, z & Px, Py, Pz

Beam Dynamics Analysis during Bunch Compression

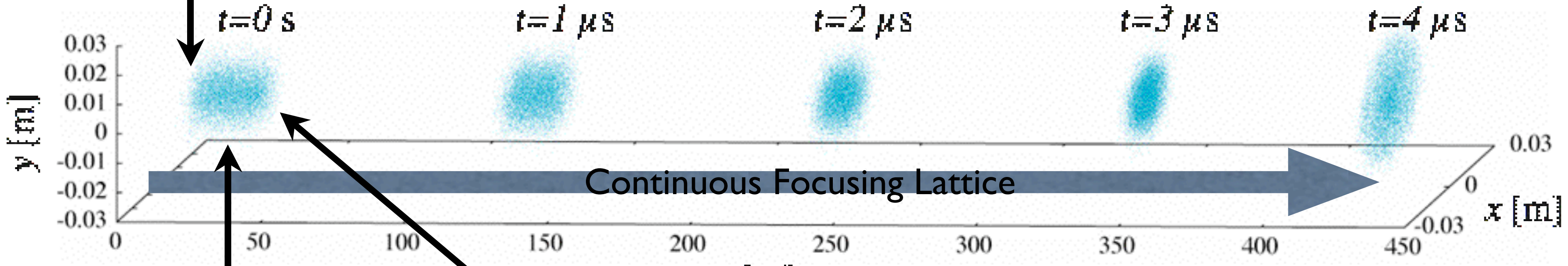


Initial Velocity Tilt of 6.6%

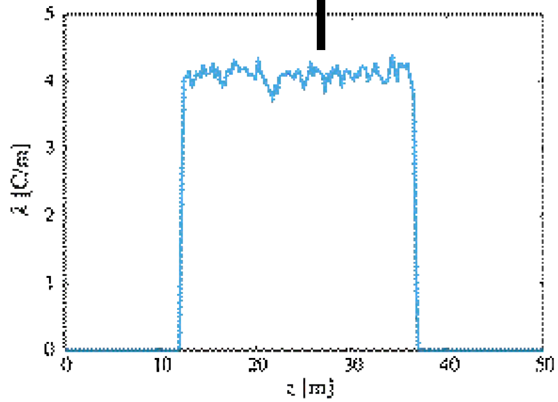
3D Particle Motion & 2D+1D Field Calculations

with Initial Gaussian & Flattop Pulse
& Linear Head-to-Tail Velocity Tilt

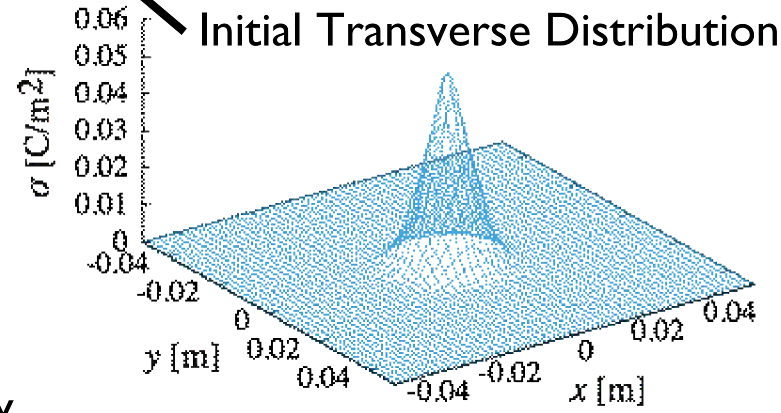
Emittance Growth due to Longitudinal-Transverse Coupling Motions



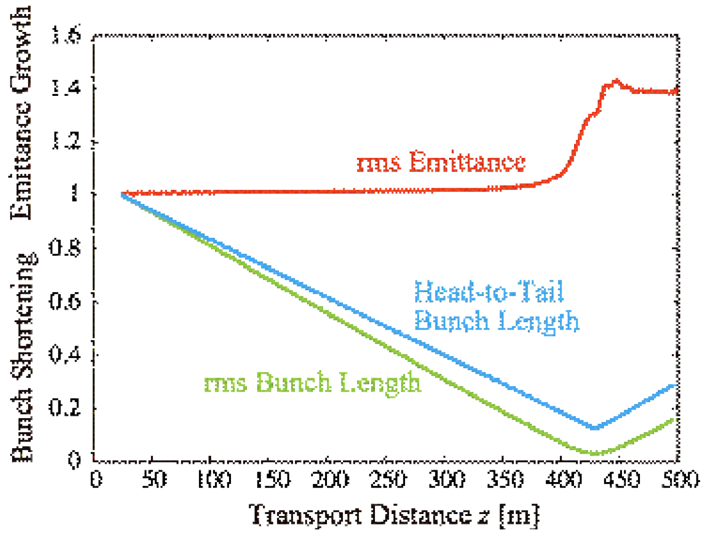
Continuous Focusing Lattice



Initial Line Charge Density



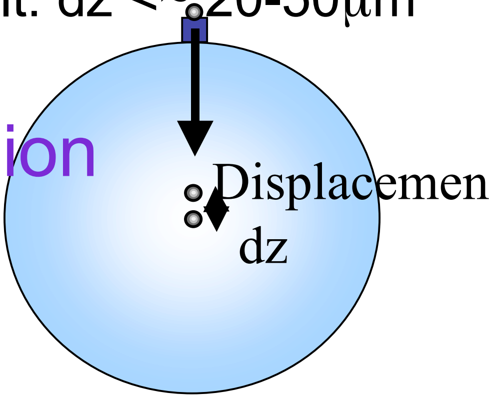
Initial Transverse Distribution



HIF Implosion &
Robust HIB Illumination

- S. KAWATA, K. MIYAZAWA, T. SOMEYA, T. KIKUCHI, Utsunomiya University, Japan,
- A.I. OGOYSKI, Varna Tech. University, Bulgaria

- Robust HIB illumination
  -> HIB radius + Illumination θ
  Result: dz <~ 200-300µm <- Previous Result: dz <~ 20-50µm
- Robust HIB illumination + target implosion
  -> Ongoing



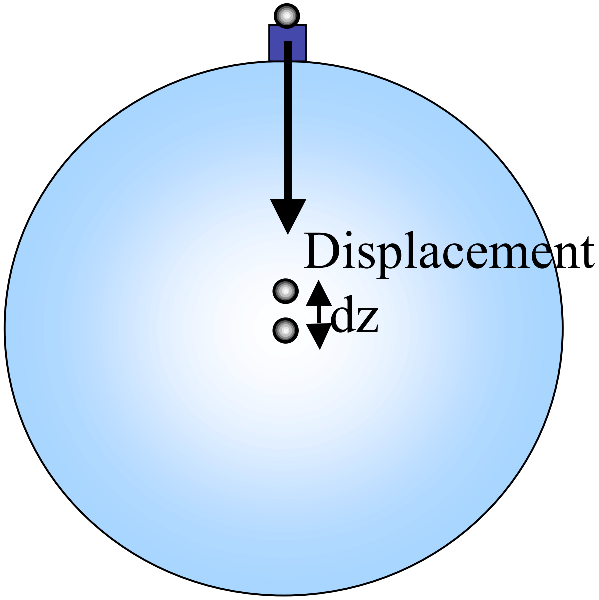
Purpose

HIBs illumination non-uniformity -> non-uniform implosion

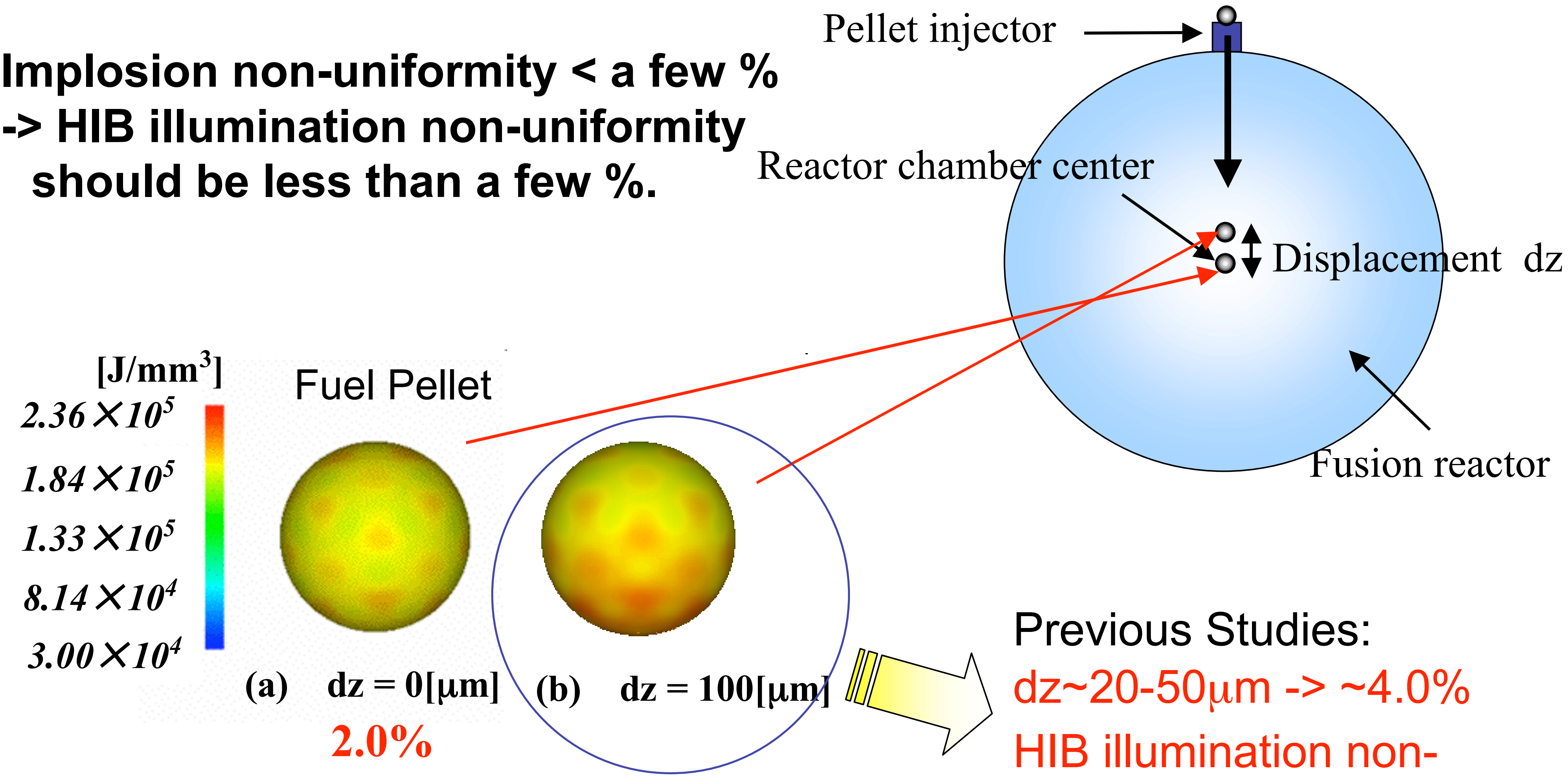
Fusion Energy output reduction

- Find out a robust HIB illumination scheme against *dz* in a direct-driven scheme

1) Detail HIB illumination analyses ←
2) Low-density foam effect on the HIB non-uniformity smoothing



Implosion non-uniformity < a few %
-> HIB illumination non-uniformity should be less than a few %.



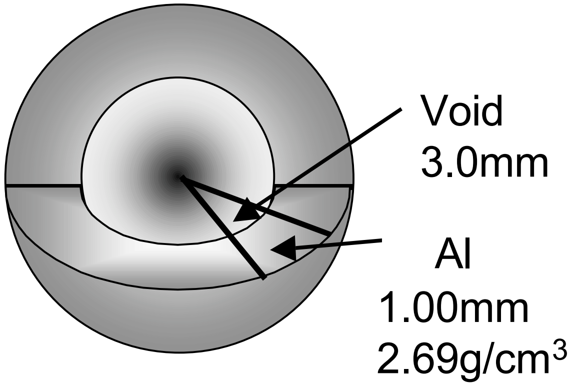
32-HIBs illumination

Previous Studies:
dz~20-50μm -> ~4.0%
HIB illumination non-uniformity

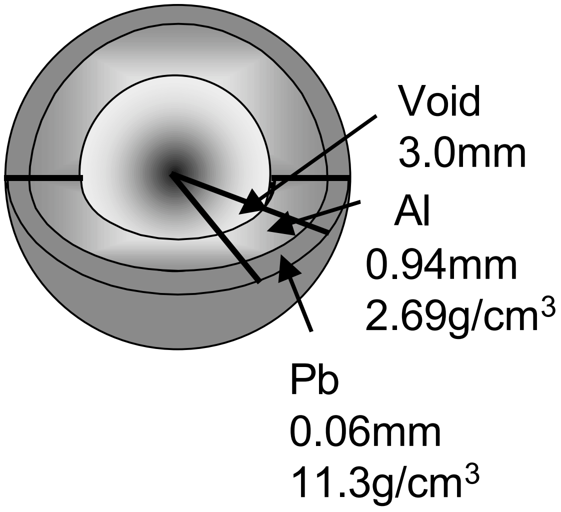
If *dz* requirement is relaxed, requirements for HIB control precision, target positioning, & monitoring precision are relaxed.
–> robust HIB illumination scheme & robust target

Parameters

- Pb^+ ion beam
- Beam number : 12, 20, 32
- Beam particle energy : 8GeV
- Beam particle density distribution : Gaussian
- Beam temperature of projectile ions : 100MeV with the Maxwell distribution
- Beam emittance : 3.2mm-mrad
- External pellet radius : 4.0mm
- Pellet material : Al, Pb + Al

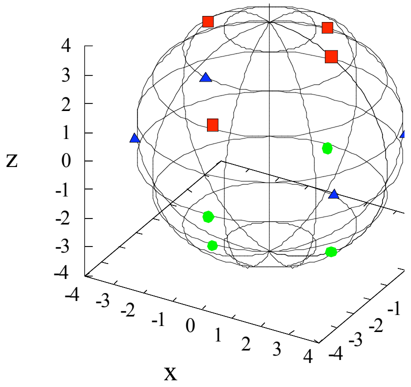


(a) Al pellet structure

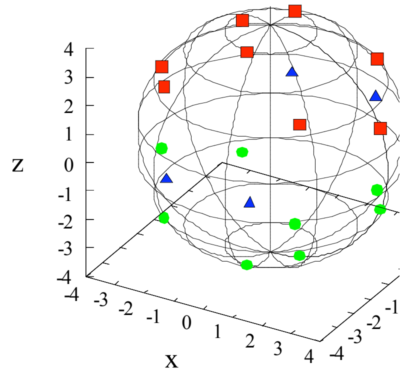


(b) Pb+Al pellet structure

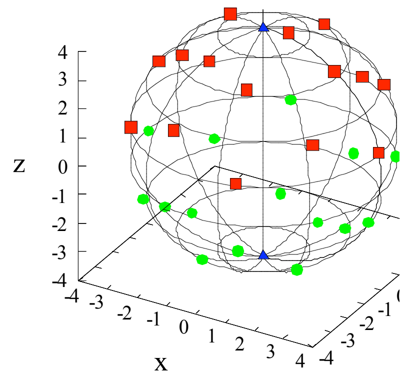
12-beam



20-beam



32-beam

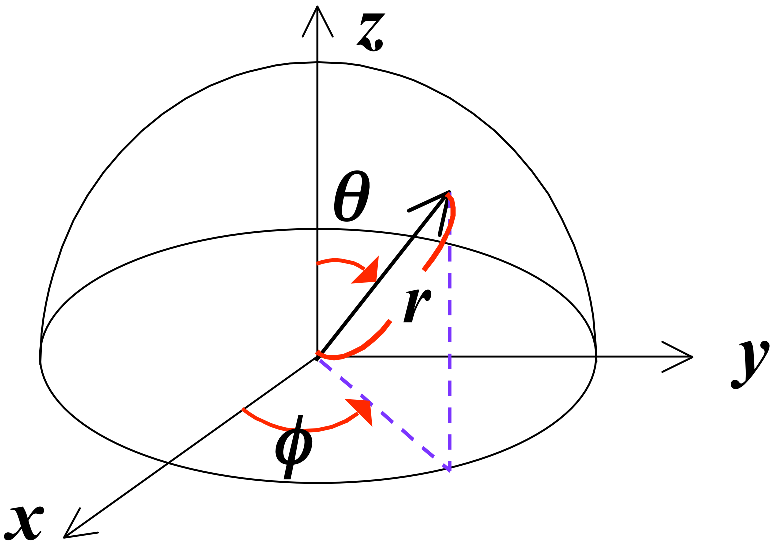


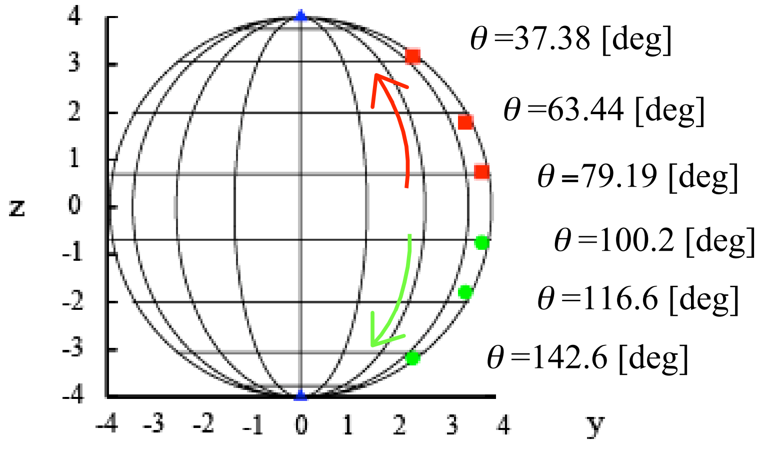
S. Skupsky and K. Lee, J. Appl
Phys. 54, 3662 (1983).

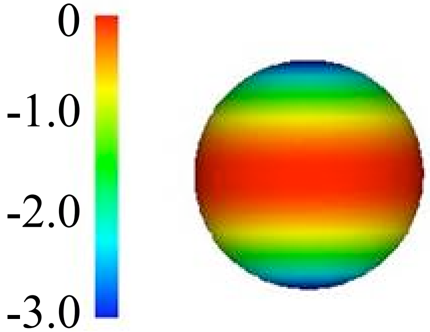
Optimization:

1) Beam radius > target radius （4.0mm at present）

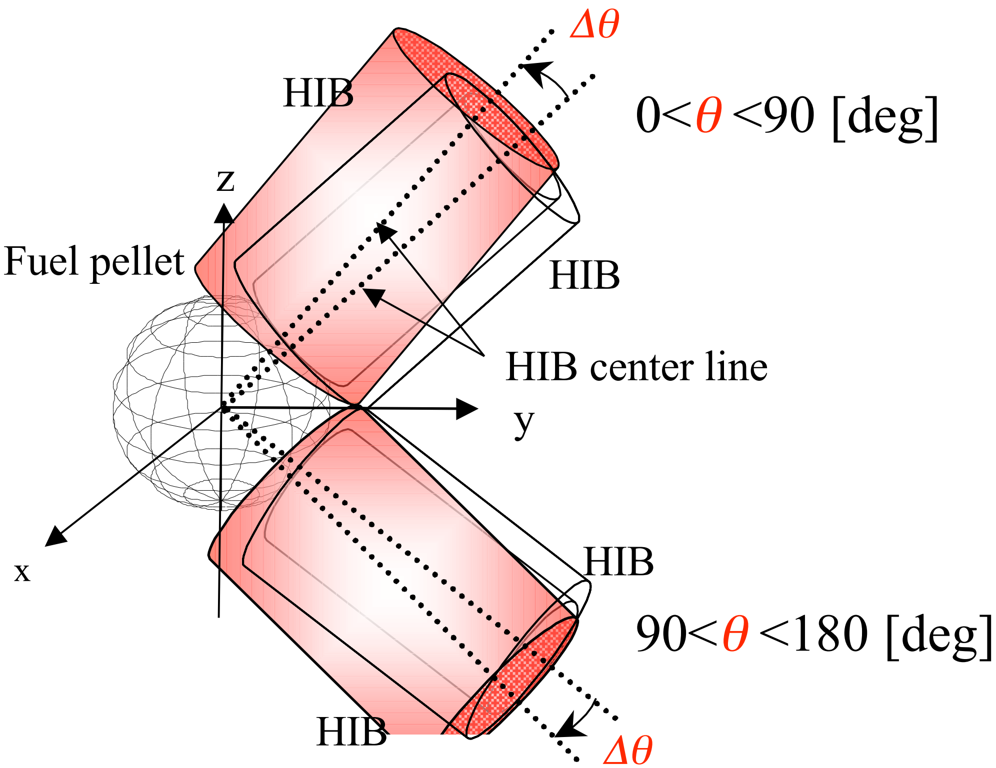
2) θ







Distribution of mode (1,0)



HIB illumination non-uniformity

Root mean square (rms)

$$\sigma_{rms} = \sum_{i}^{n_r} w_i \sigma_{rms_i} \qquad \sigma_{rms_i} = \frac{1}{\langle E \rangle_i} \sqrt{\frac{\sum_j^{n_\theta} \sum_k^{n_\phi} \left(\langle E \rangle_i - E_{ijk} \right)^2}{n_\theta n_\phi}}$$

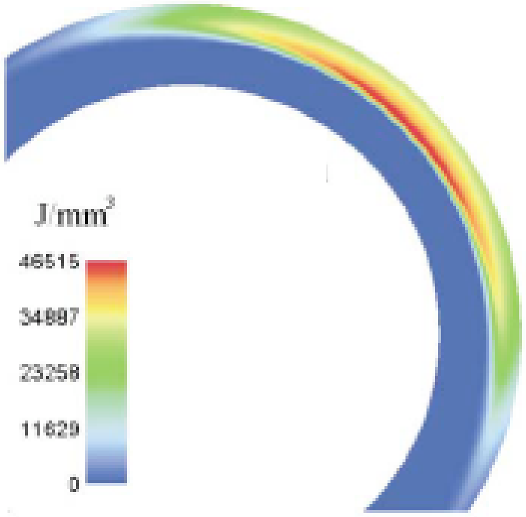
n_r, n_θ, n_ϕ : Mesh total number

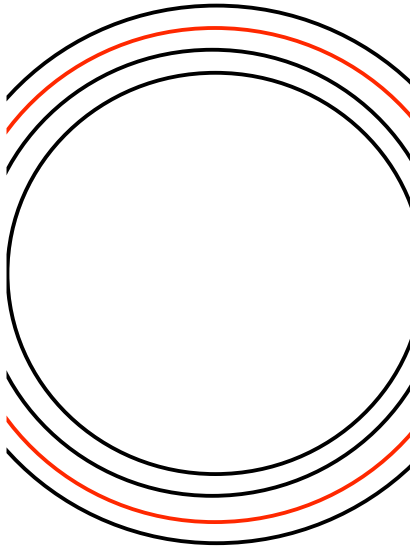
$\langle E_i \rangle$: Averaged Energy deposition at i-th layer

E_i : Total energy deposition at i-th layer

E : Total Energy deposition

$$w_i = \frac{E_i}{E}$$





Spectrum analysis

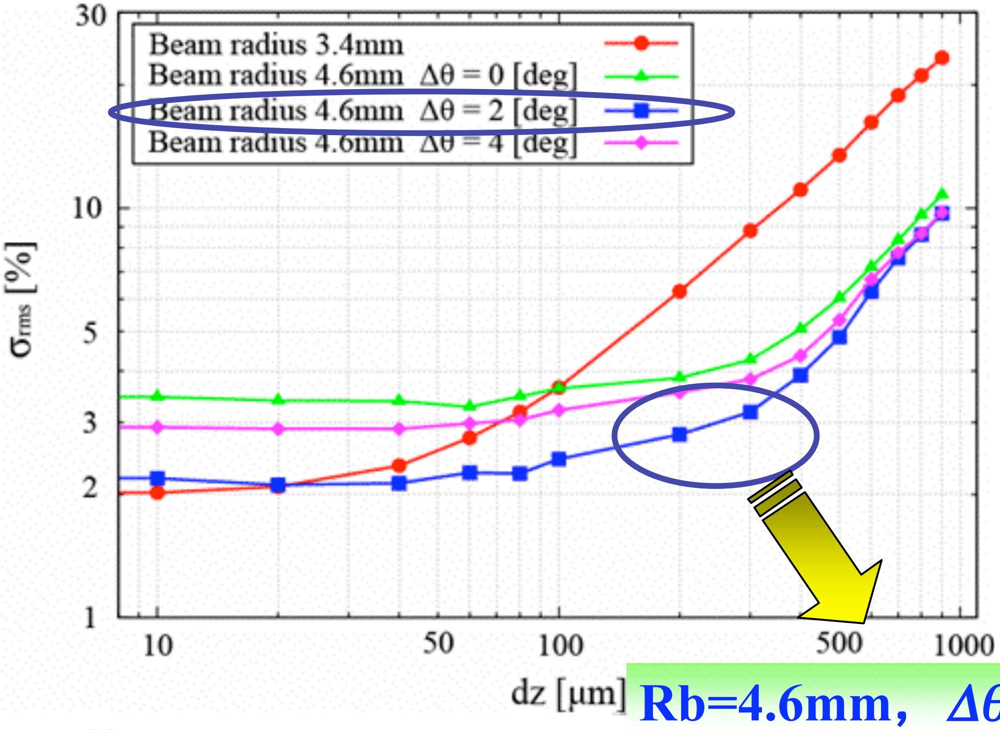
$$S_n^m = \frac{1}{4\pi} \int_0^{\pi} \sin\theta d\theta \int_0^{2\pi} E(\theta,\phi) Y_n^m(\theta,\phi) d\phi$$

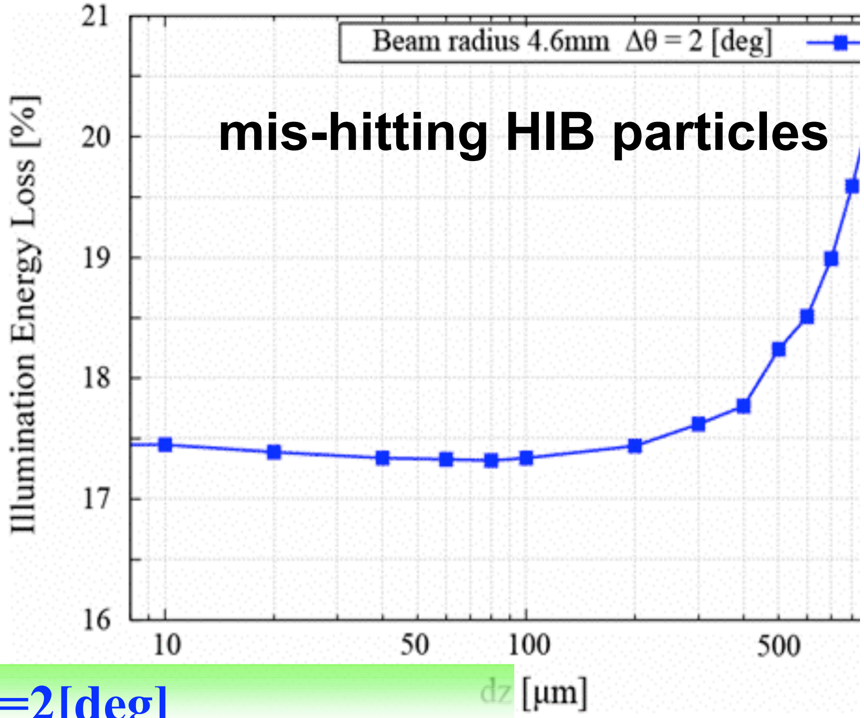
$E(\theta,\phi)$:Energy deposition at each mesh

$$Y_n^m(\theta,\phi) = P_n^m(\cos\theta) e^{im\phi}$$

(n,m): mode number

32-beam, Al target, External pellet radius 4.0mm

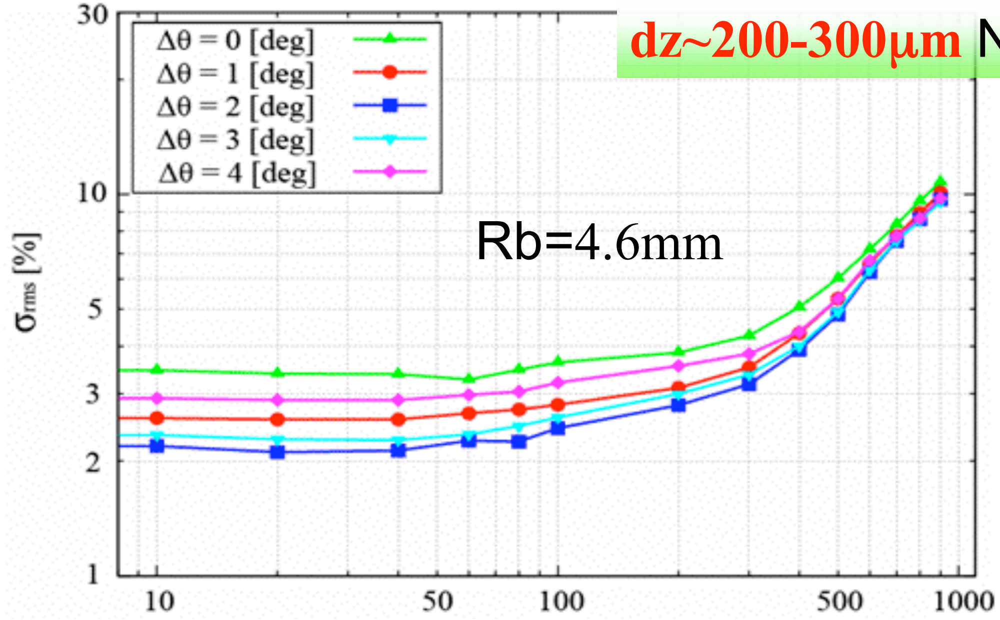




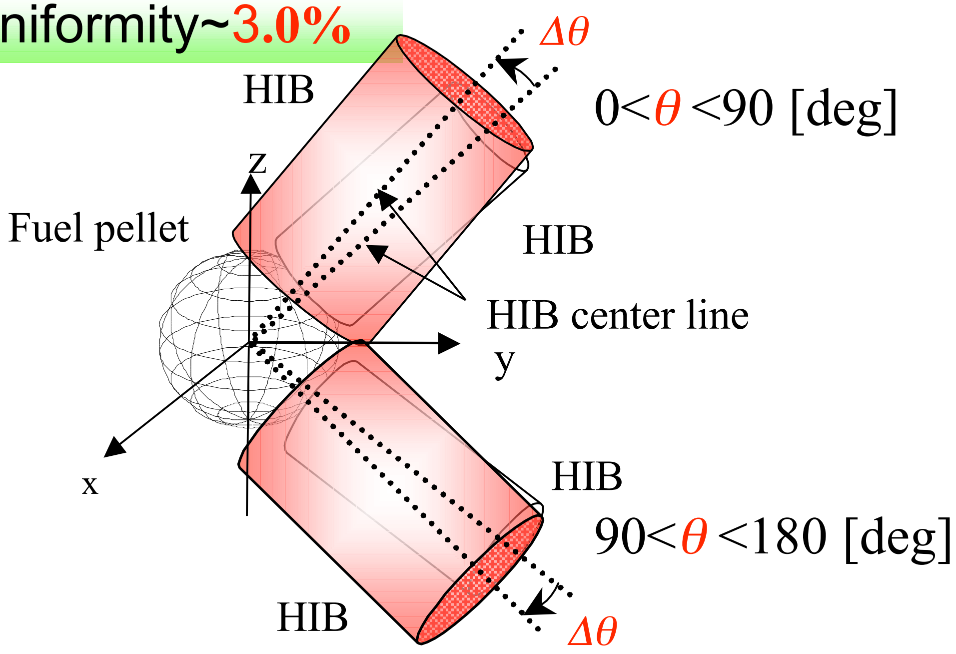
mis-hitting HIB particles

Rb=4.6mm, $\Delta\theta$ =2[deg]

dz~200-300μm Non-uniformity~**3.0%**

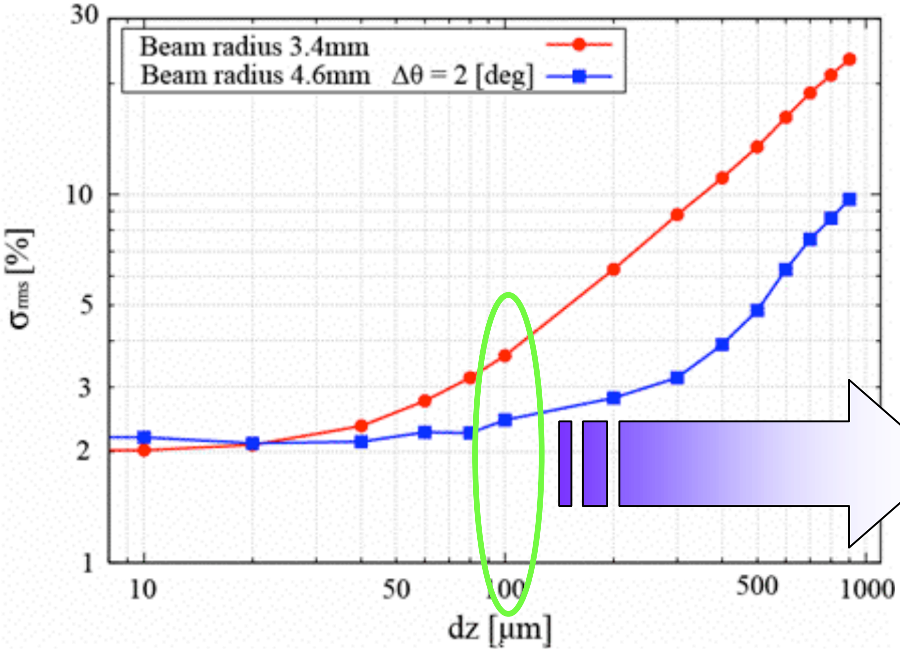


Rb=4.6mm



32-beam, **Al target**

External pellet radius 4.0mm

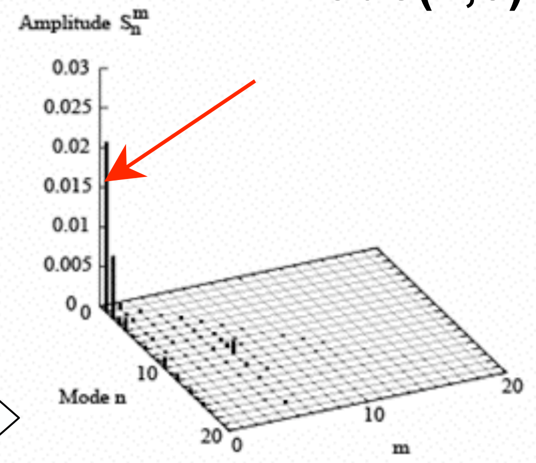


Rb < Target radius
Conventional Scheme

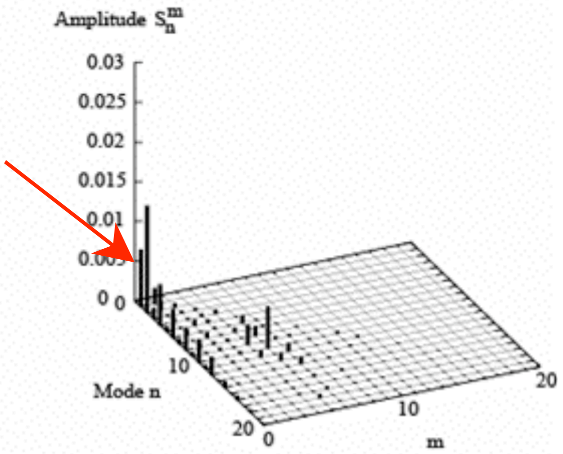
Rb=4.6mm > target radiu
Δθ = 2 degree
New Scheme

(a) Bragg peak, Beam radius 3.4 mm, Al target

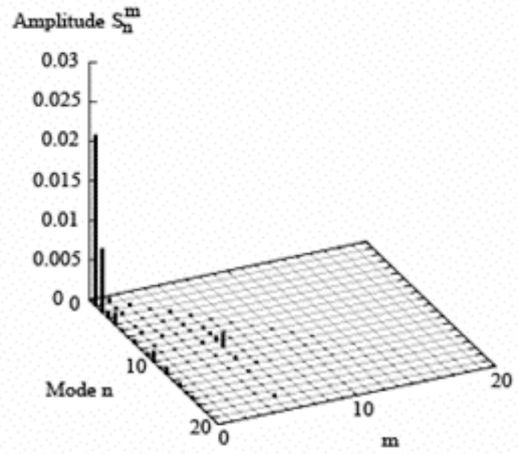
Mode(1,0)



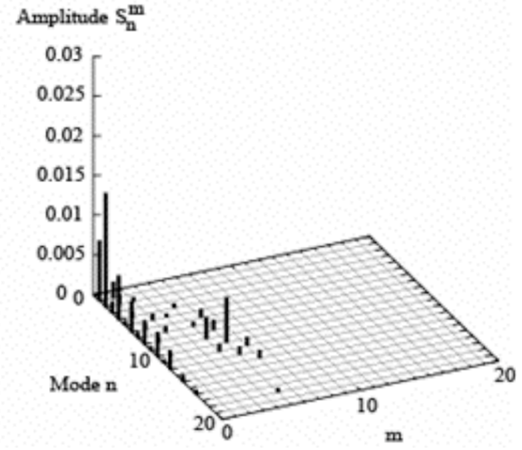
(d) Bragg peak, Beam radius 4.6 mm, Δθ = 2 degree, Al target

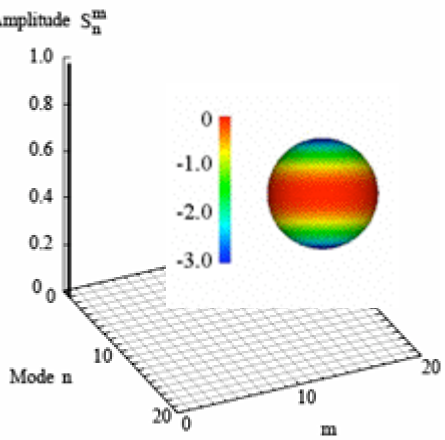


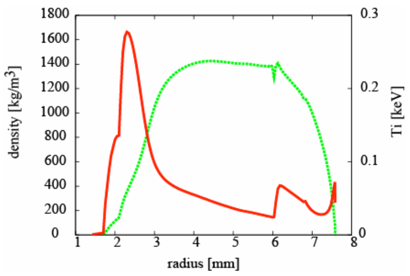
(c) Global, Beam radius 3.4 mm, Al target



(d) Global, Beam radius 4.6 mm, Δθ = 2 degree, Al target



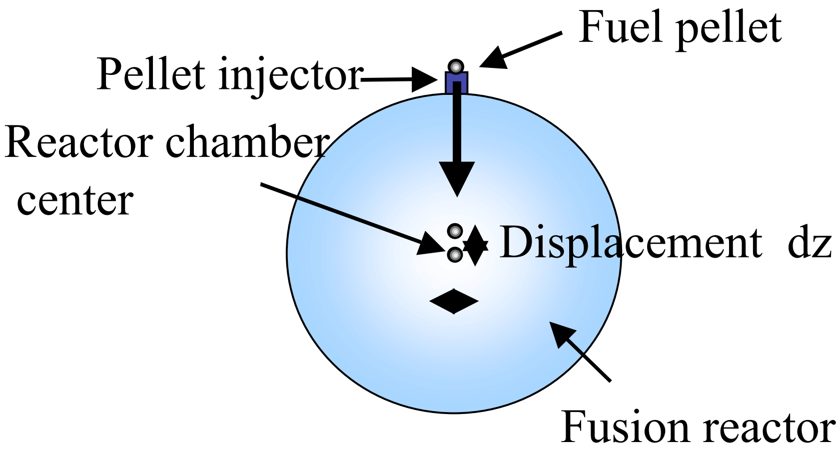




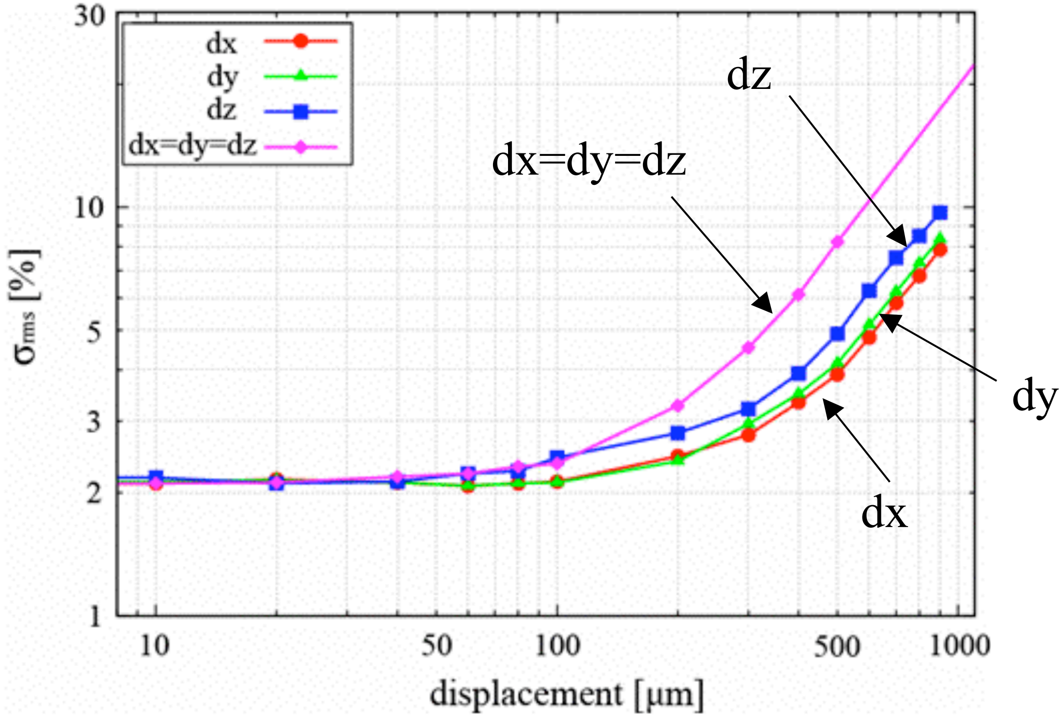
Distribution of mode (1,0)

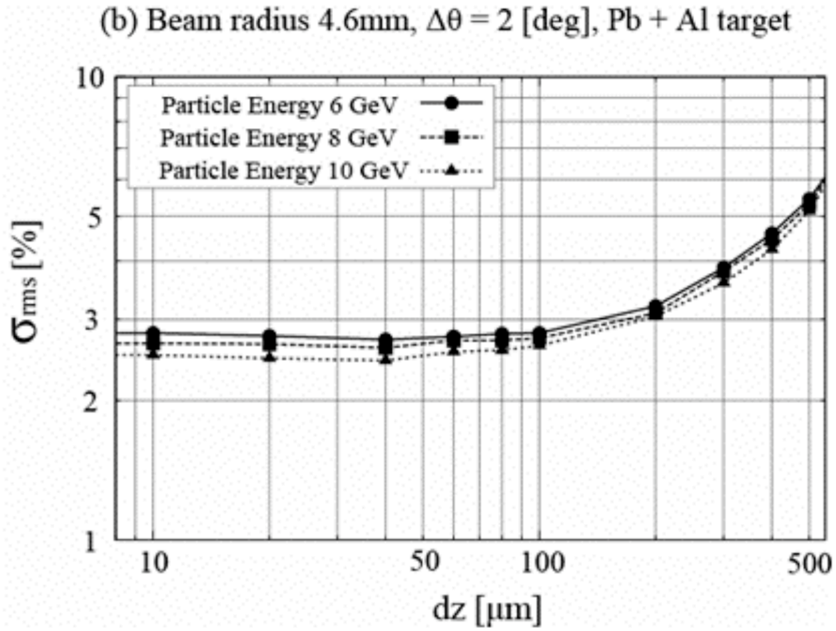
dz = 100 [μm]

32-beam
Al target
External pellet radius 4.0mm



Beam radius 4.6mm $\Delta\theta = 2$ [deg]





dx=dy=dz~200-300μm -> non-uniformity 3.0-4.0%

Implosion Simulation including HIB illumination ->Ongoing project

target

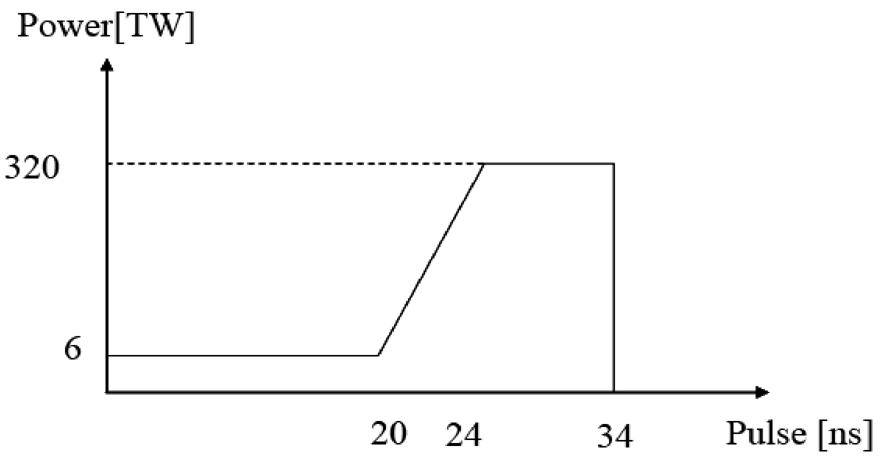
- With foam (0.5 mm thickness)
- Without foam

Radiation transport

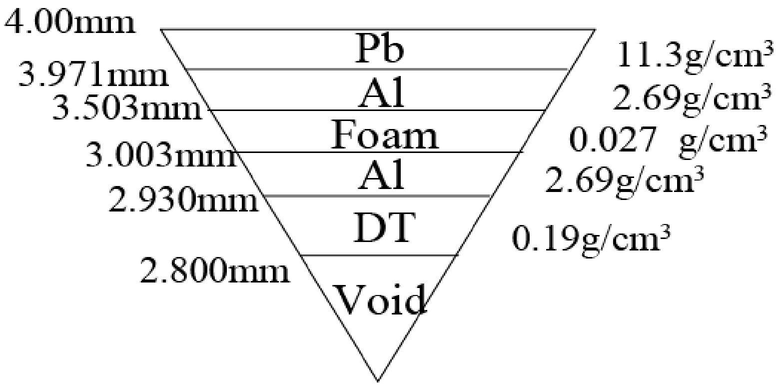
- ON
- OFF

32-HIBs illumination

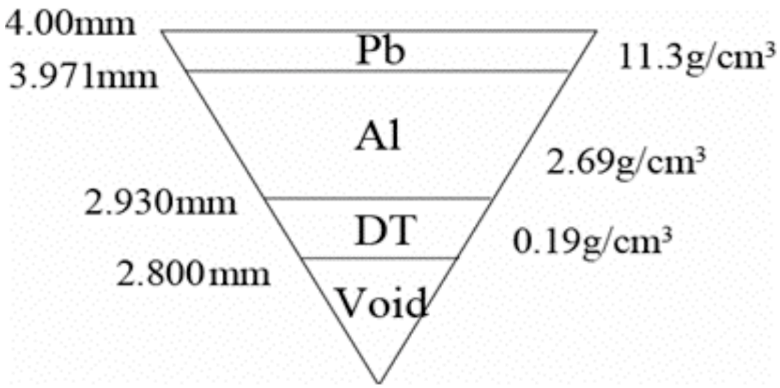
pulse



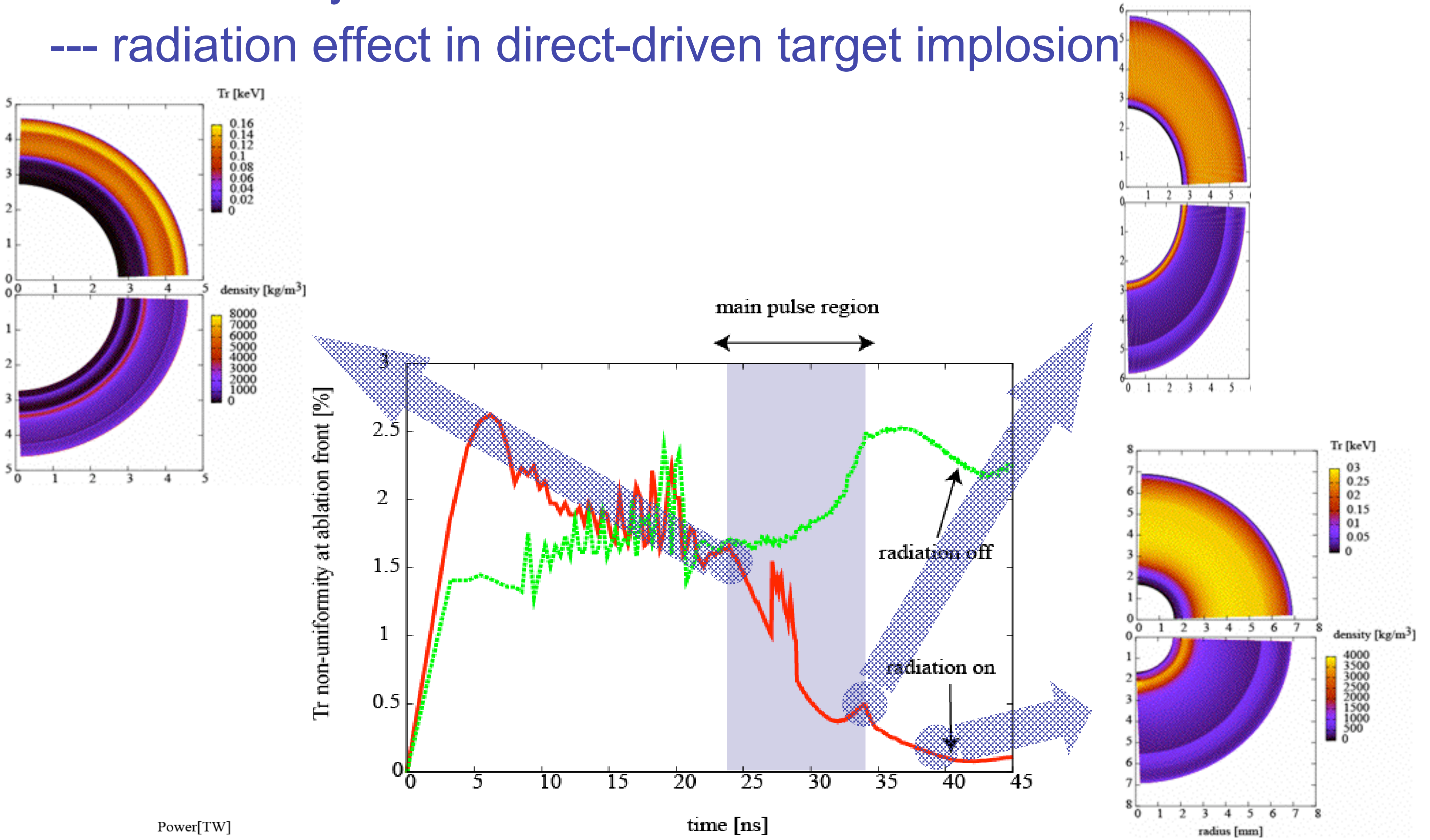
0.5 mm foam

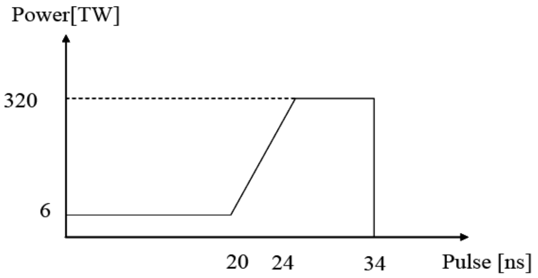


Without foam



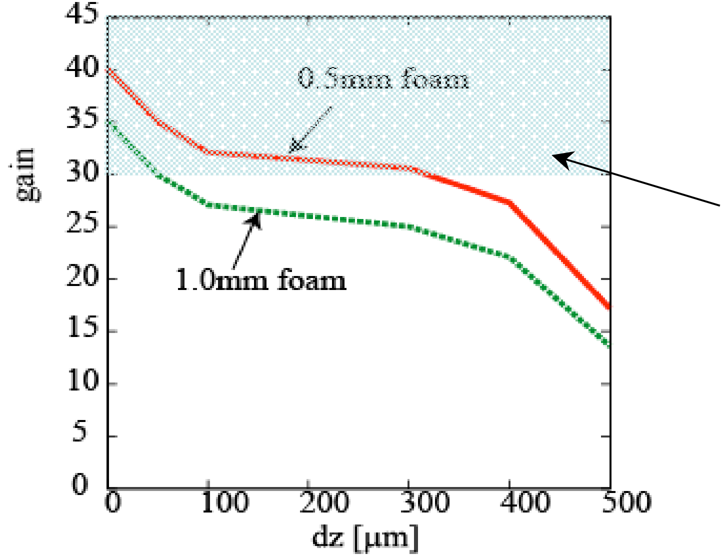
Non-uniformity check
--- radiation effect in direct-driven target implosion





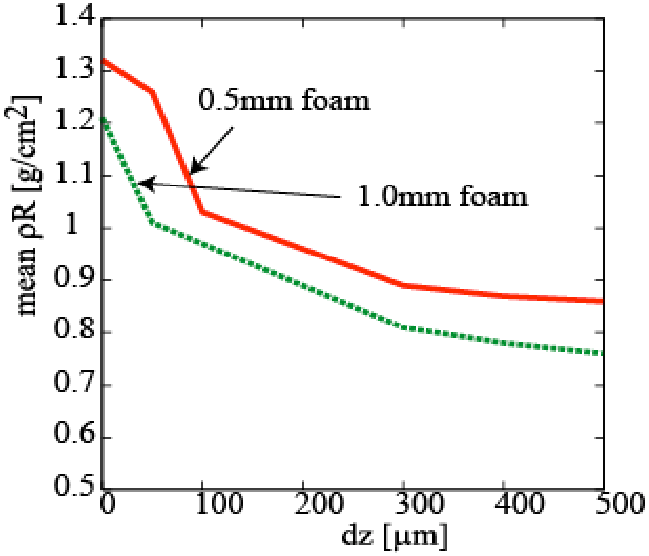
Foam Target

Gain curve

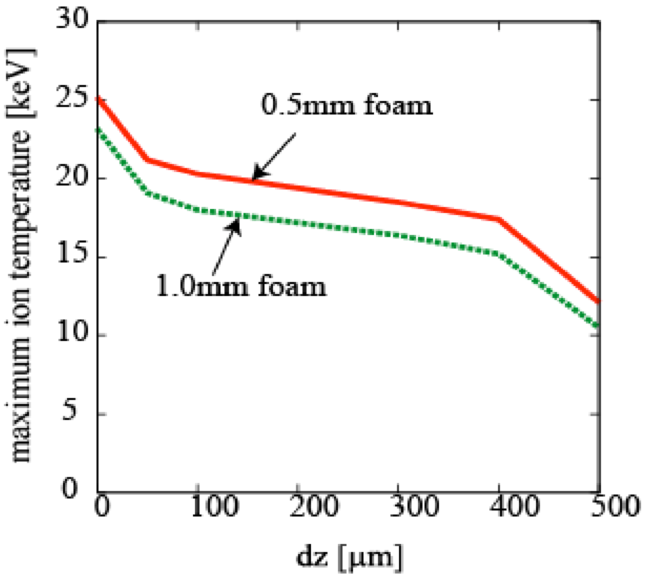


Required gain region

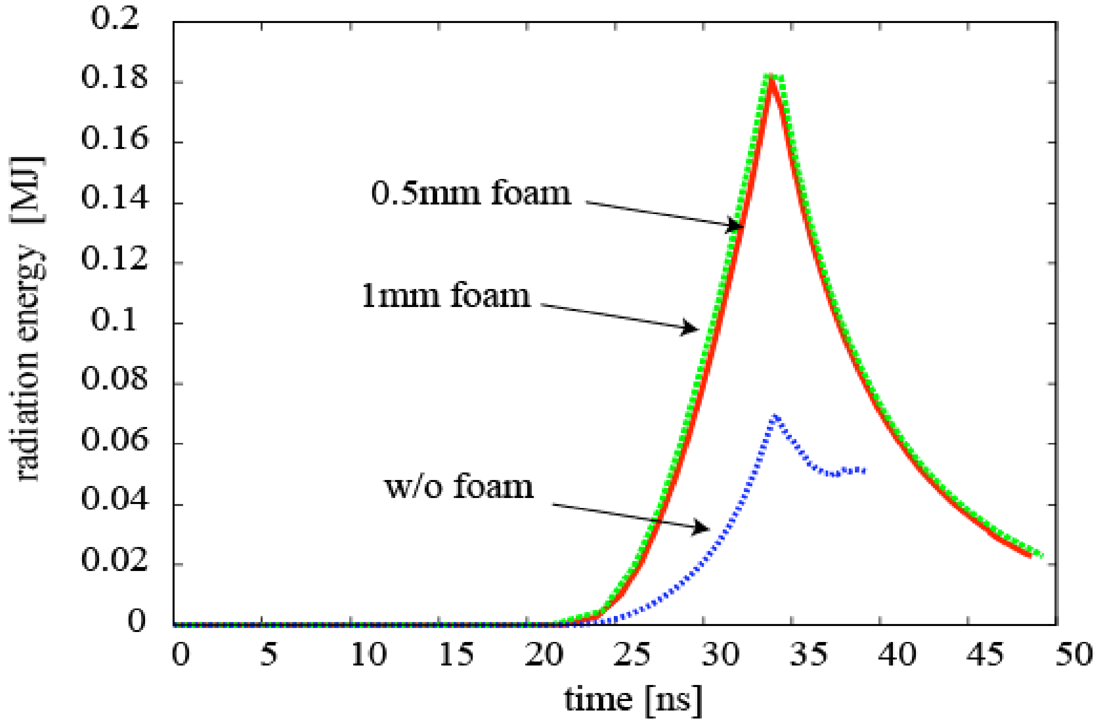
Mean ρR



Maximum ion temperature



Radiation energy at low density region



*Conversion efficiency (Beam energy to radiation energy)

- 0.5 mm foam : ~ 4.5 %
- 1.0 mm foam : ~ 4.5 %
- w/o foam : ~ 1.5 %

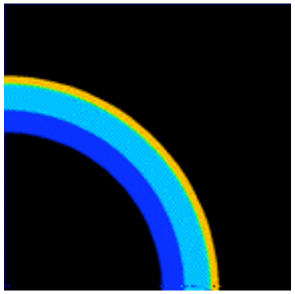
Mixture of direct and indirect mode

Results

Detail HIB illumination analyses

- ☐ **New Robust HIB illumination scheme was found.**
  -> dz ~ 200 ~ 300 μm

- ☐ **Ongoing: Implosion simulation + HIB detail Illumination**
  -> Preliminary results: Even in a direct-driven target implosion, radiation smoothing effect is expected. A foam layer may help to enhance the smoothing.



HIF Direct-Drive Targets / R-T Instability

S. Kawata, T. Kikuchi
Utsunomiya University

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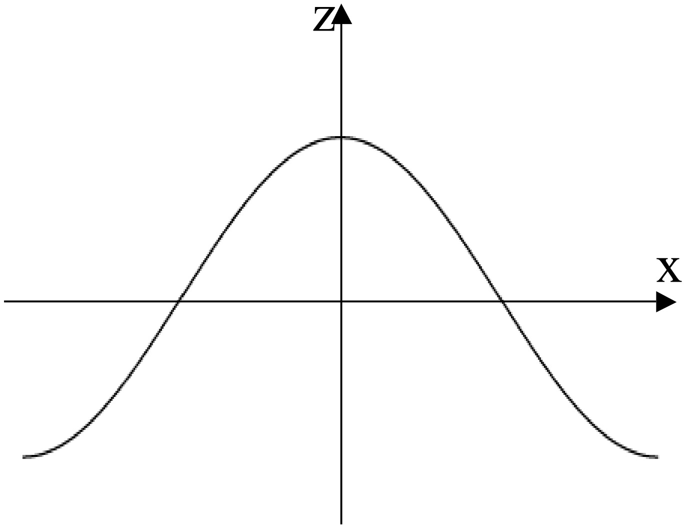
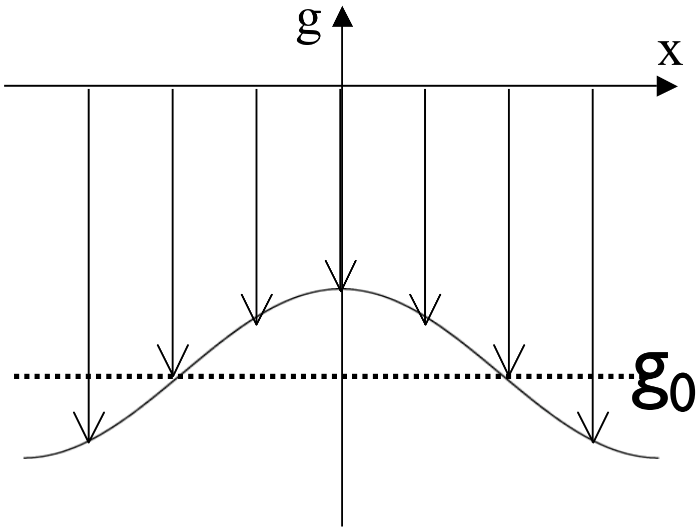
2) HIF Implosion & Robust HIB illumination
3) Rayleigh-Taylor Instability Study in HEDP

Beam-induced g has a non-uniformity of δ g



$$g(x,y,z,t) = g_0 + \delta g(x,y,z,t)$$

$$\delta g(x,y,z,t) = g_1 f(x,y) exp(-\beta|z|)\Gamma(t$$



$$w = \Phi\, exp(ik_{xg}x + ik_{yg}y)exp(-k|z|)exp(\gamma$$

$$- g_1\, exp(ik_{xg}x + ik_{yg}y)exp(-$$

$$= w_0 + w_1$$

Effect of δ g

$$R\left(= \left(w_1 / w_0\right)\times 100\,[\%]\right)$$

k	a=0.005	a=0.01
5	25.9	12.9
10	23.6	11.8
50	16.0	8.00
100	11.9	6.00
500	3.50	1.70
1000	1.40	0.70

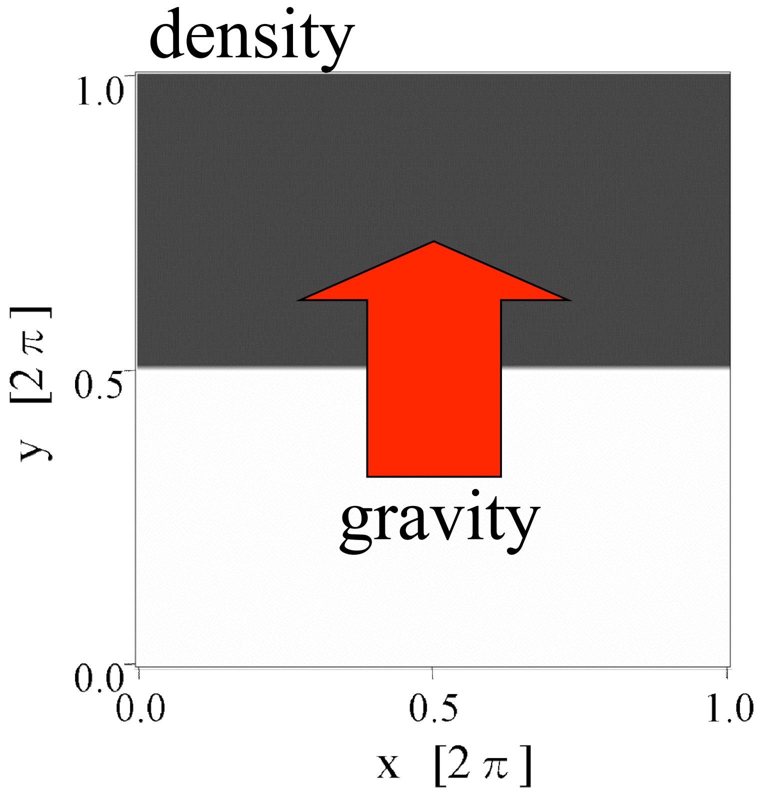
parameter

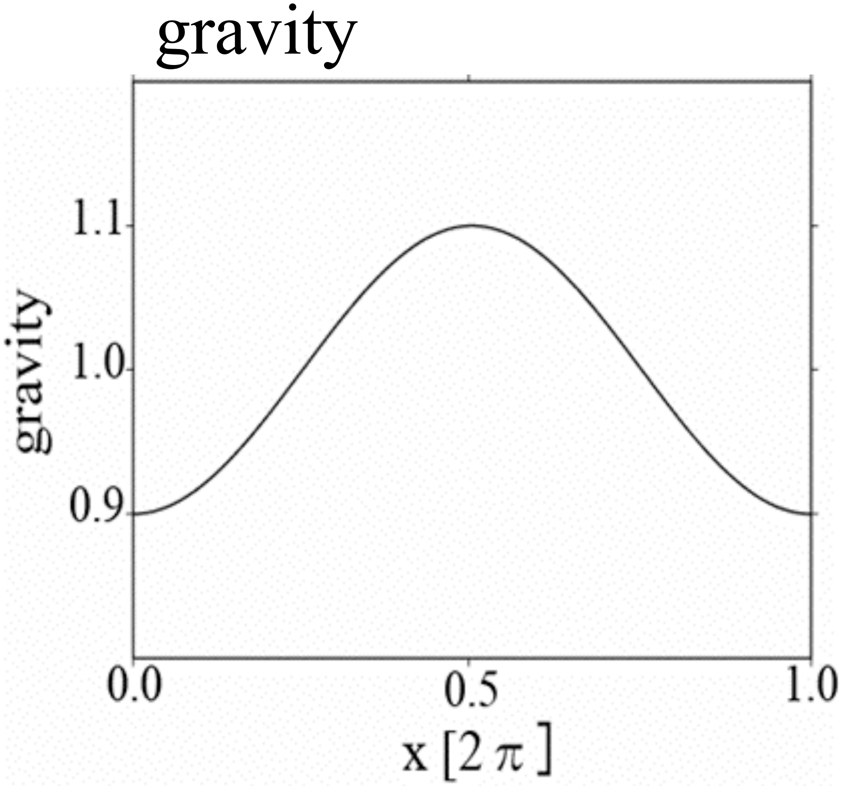
$$g = g_0 + g_1 \qquad g_0 = 1.0\times 10^{13} \quad \left(m / s^2\right) \qquad g_1 = 0.1 g_0$$

$$\Phi = Initial\ \ perturbation\ amplitude = a\times 6.185\times 10^{5} \quad \left(m\right.$$

$$t = 1.0 \quad \left(n\,sec\right)$$

Single Mode Simulation [constant gravity]





parameter

ρ_{High} : 10

ρ_{Low} : 3

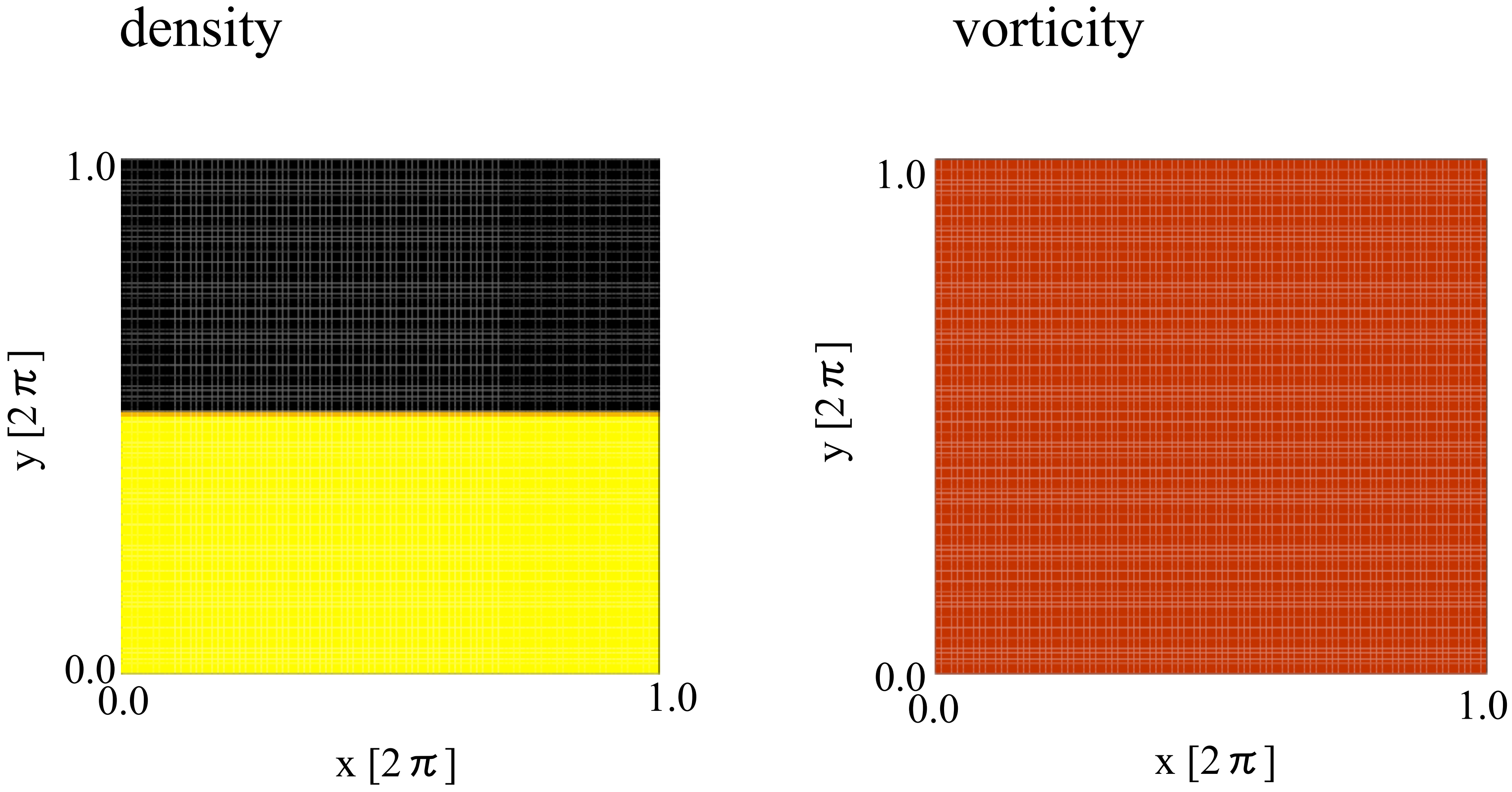
$g : g_0 + 0.1 g_0 \sin(kx)$

$g_0 : 1$

$k : 1$

Single Mode Simulation [constant gravity]

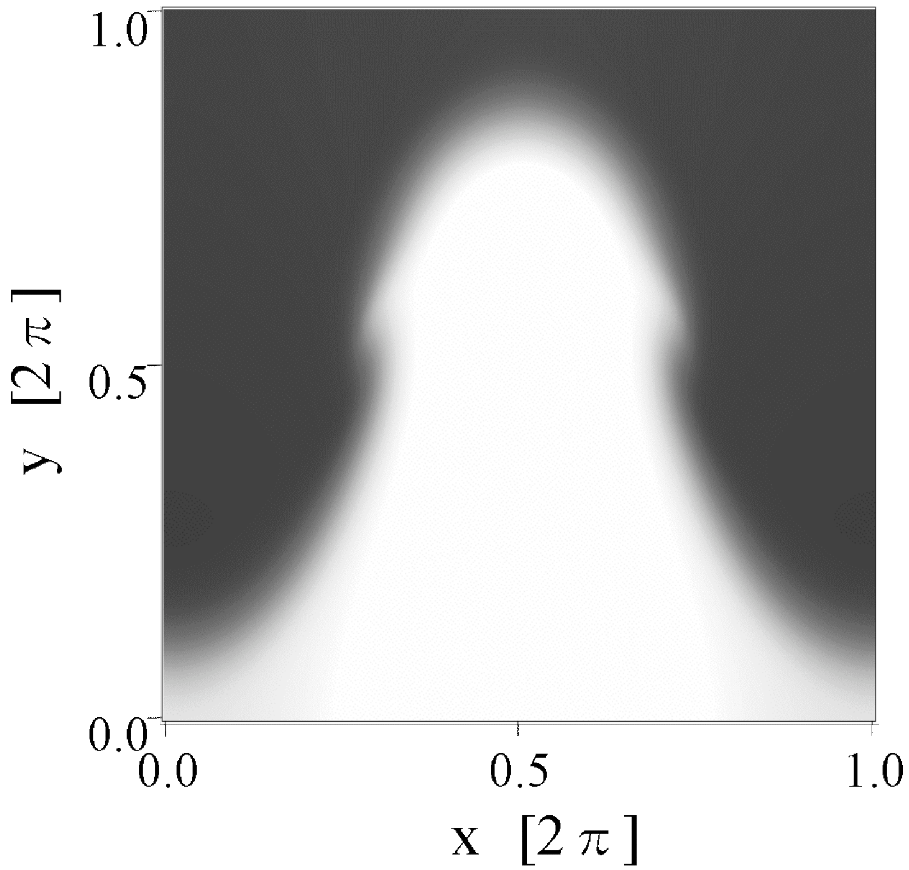
t=0~6 [1/γ]



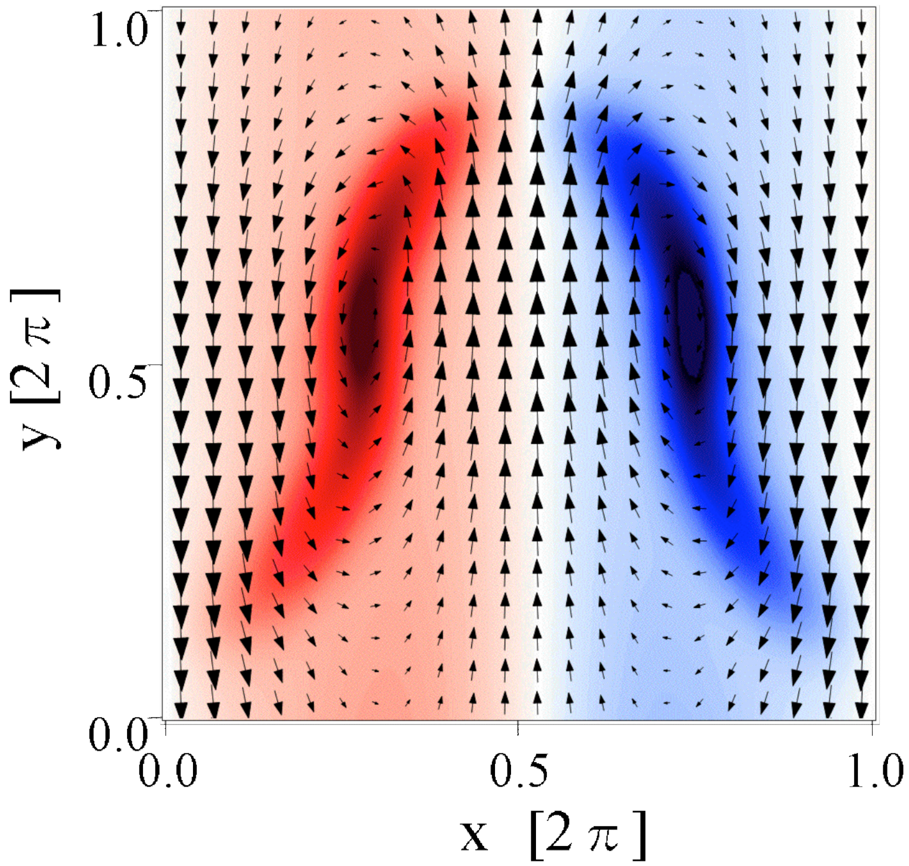
Single Mode Simulation [constant gravity]

t=5 [1/γ]

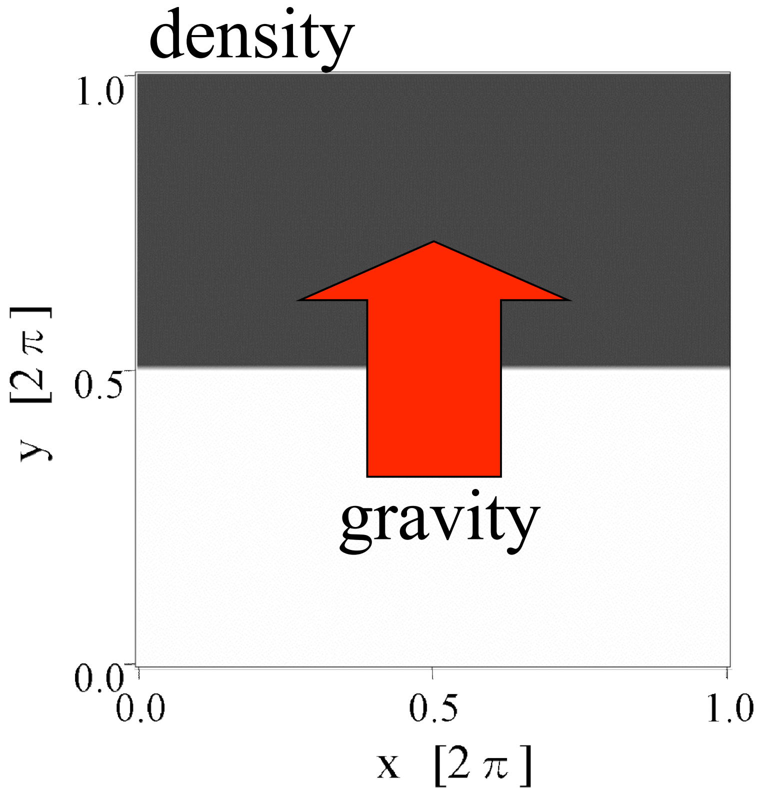
density

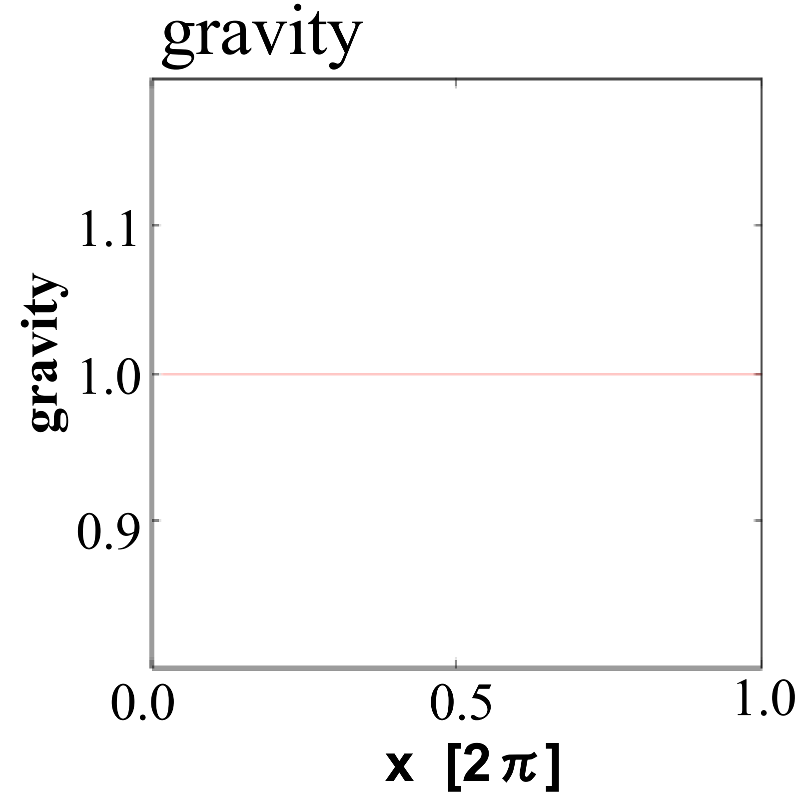


vorticity



Single Mode Simulation [oscillation gravity]





parameter

$\rho_{High} : 10$

$\rho_{Low} : 3$

$g : g_0 + 0.1 g_0 \sin(kx) \sin(2\pi f t)$

$g_0 : 1$

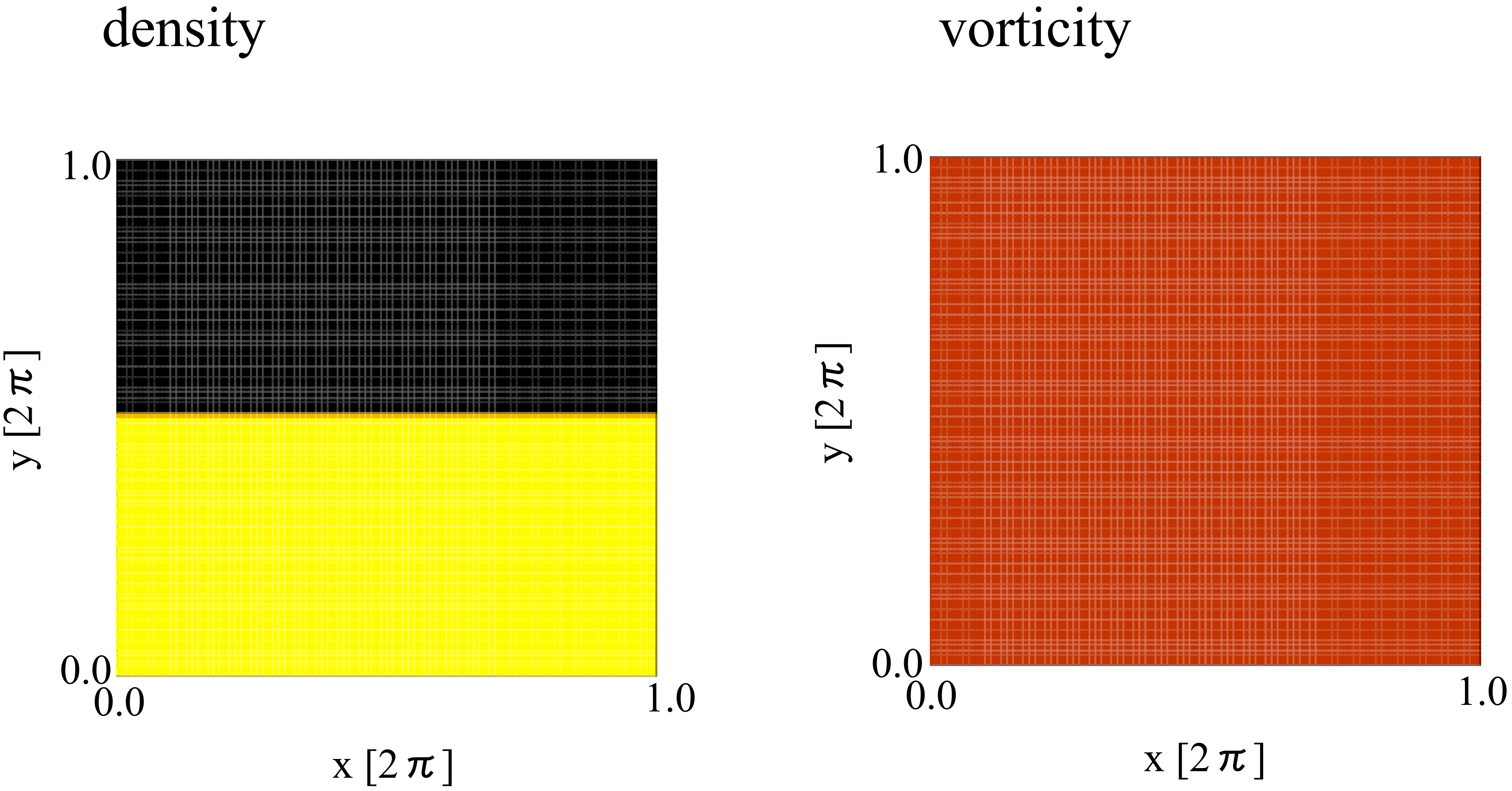
$k : 1$

$f : \gamma \quad \left(\gamma = \sqrt{g_0 k}\right)$

$$ex.\ g_0 = 10^9 \left[m/s^2\right], k = 1 \left[1/mm\right] \rightarrow f = 10^6 \left[Hz\right]$$

Single Mode Simulation [oscillation gravity]

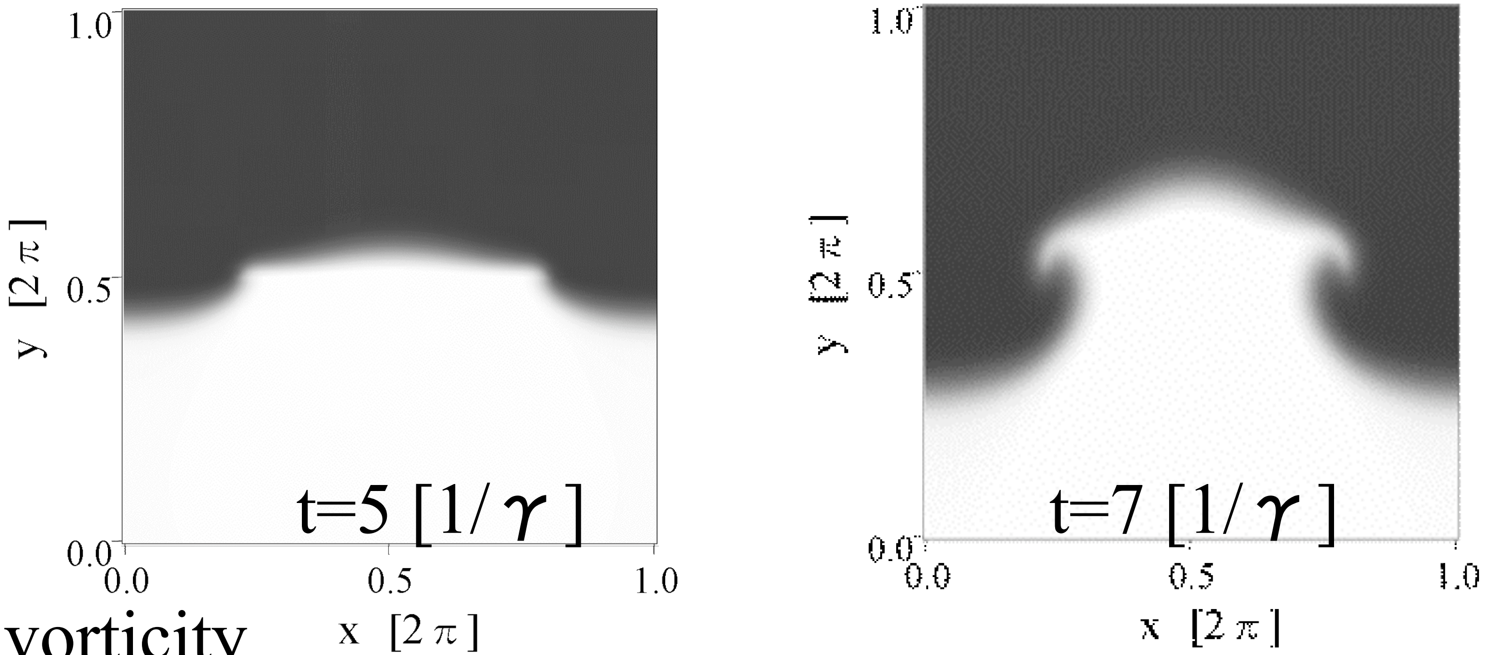
t=0~10 [1/γ]



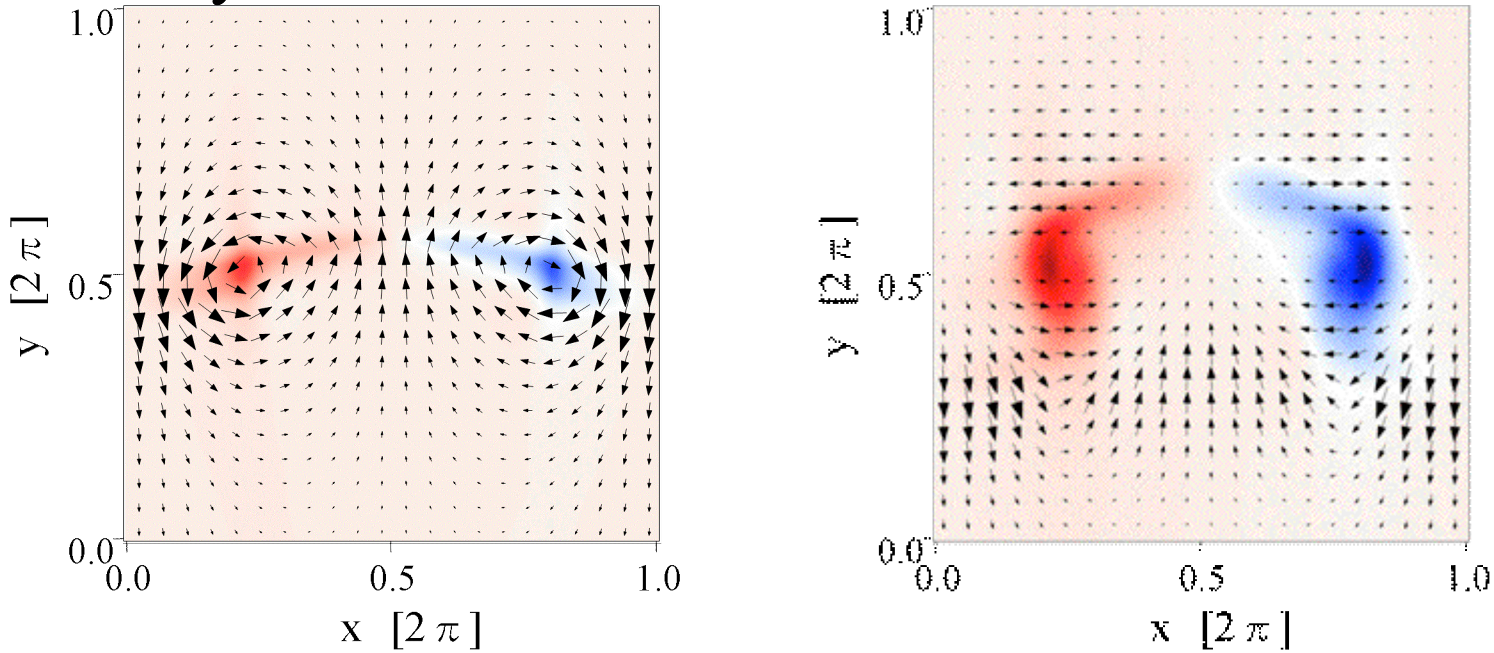
Single Mode Simulation

oscillation (1[MHz])

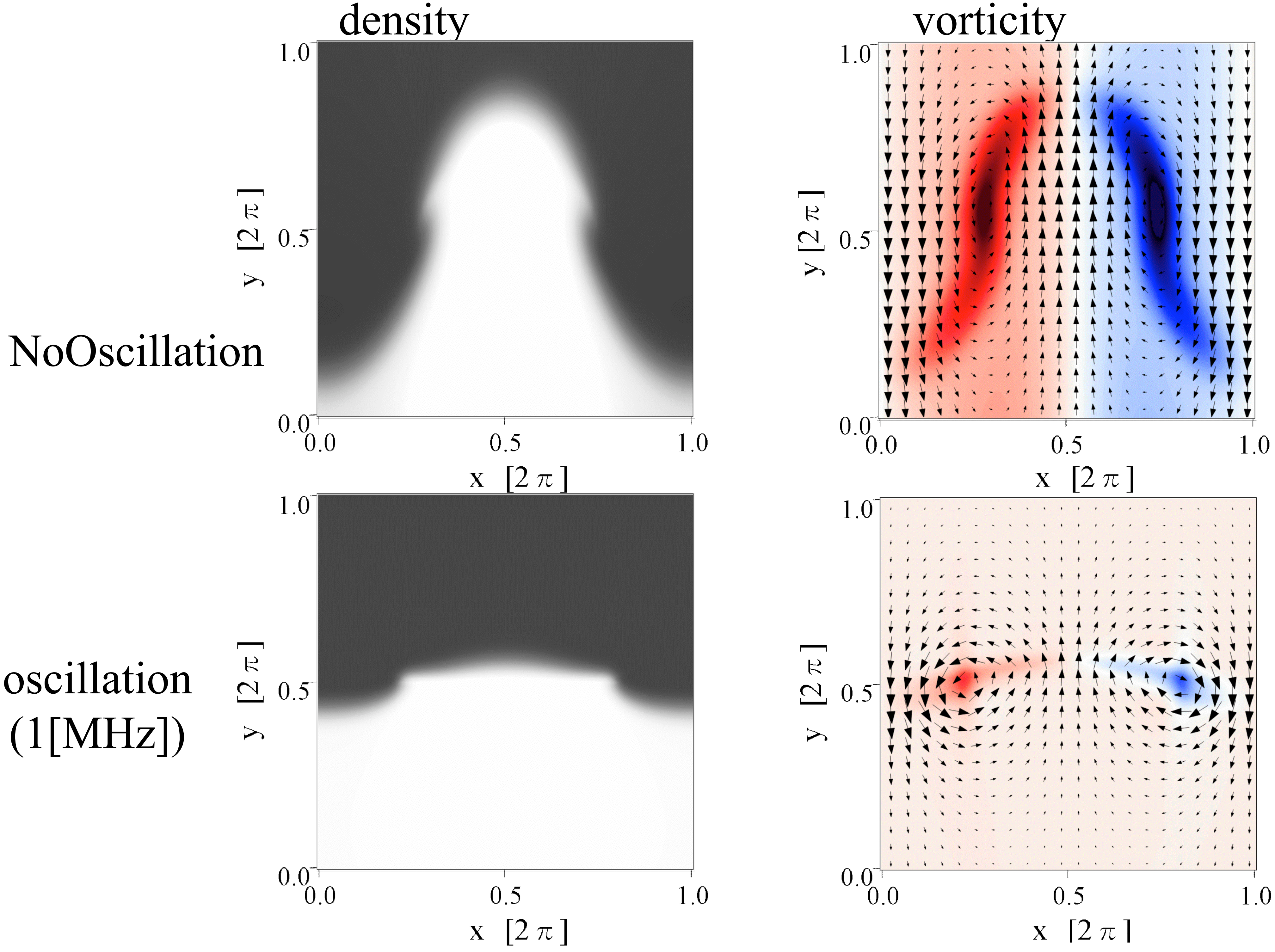
density



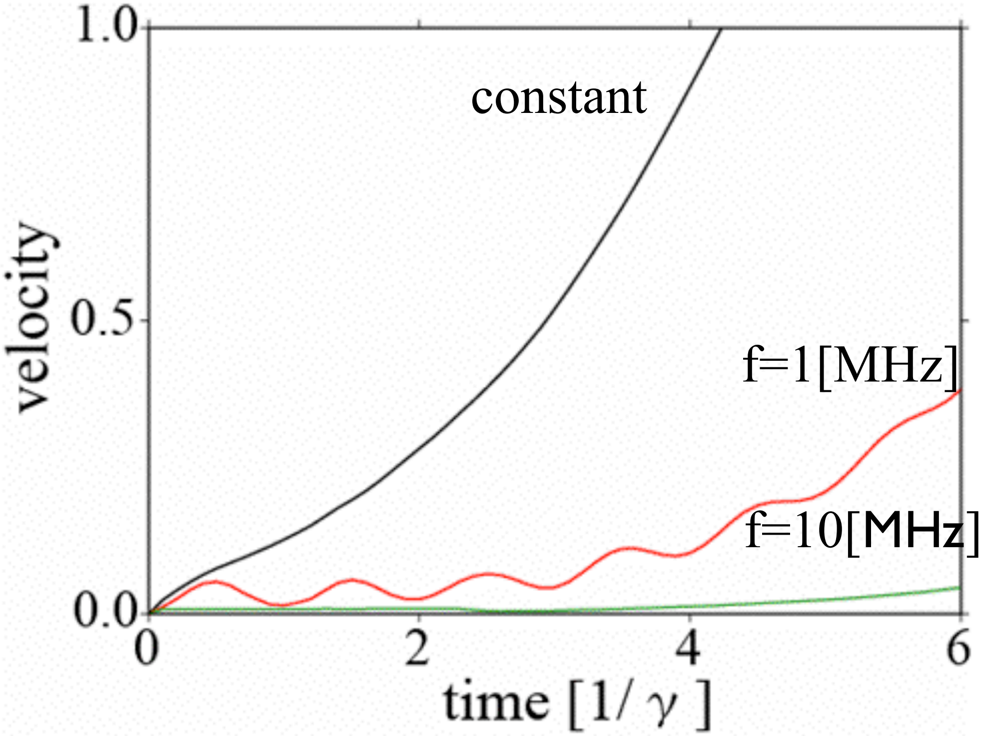
vorticity

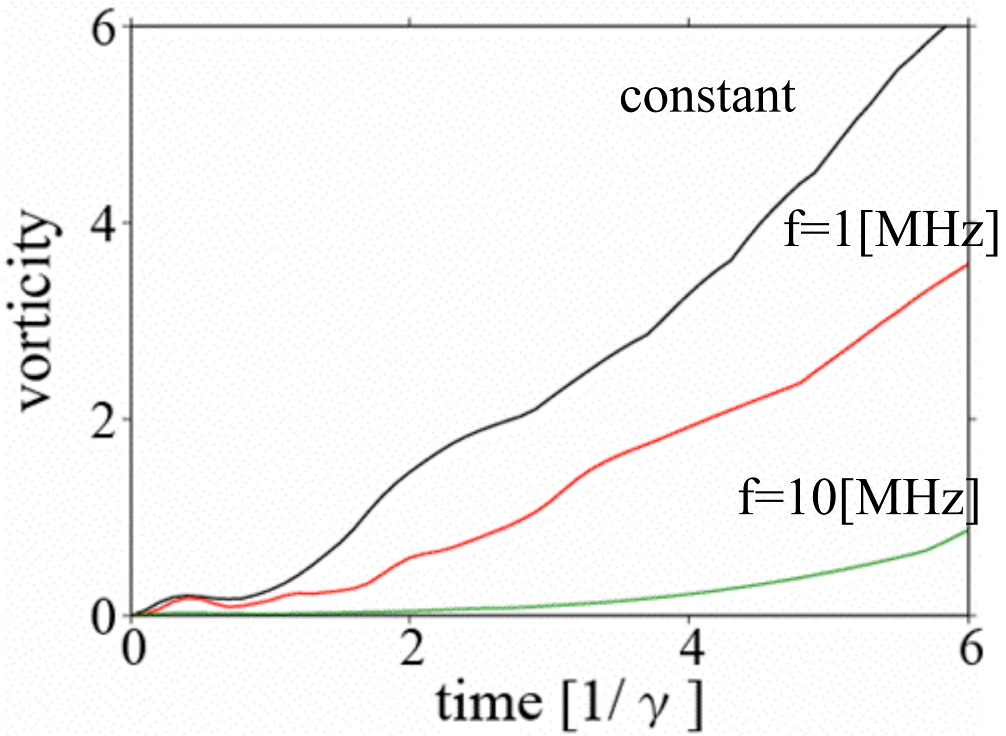


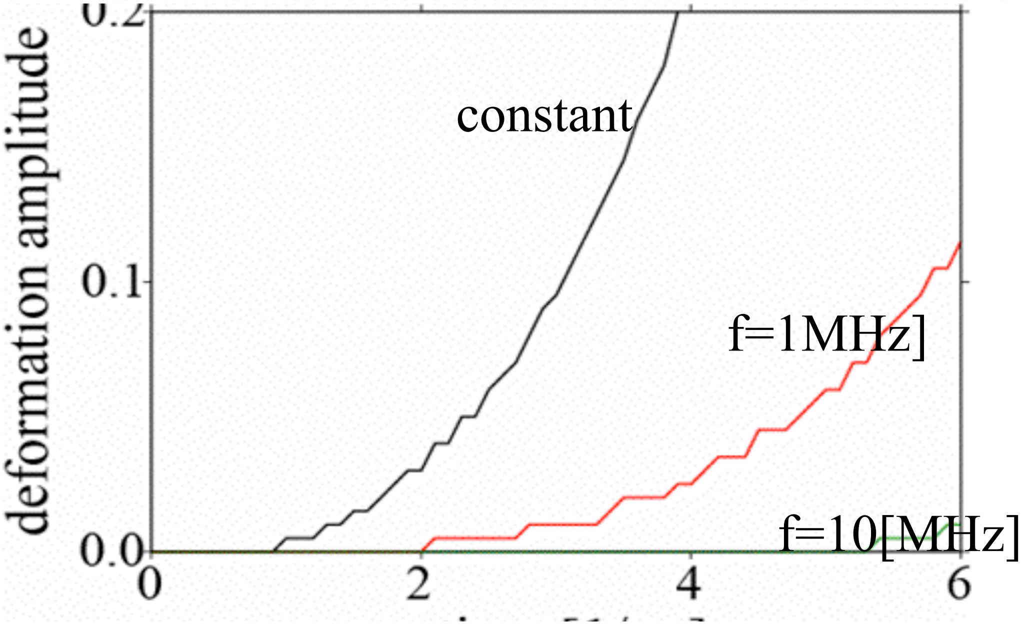
Single Mode Comparison (t=5 [1/γ])



Single Mode Comparison (passage of time)







$time[1/\gamma]: 5$

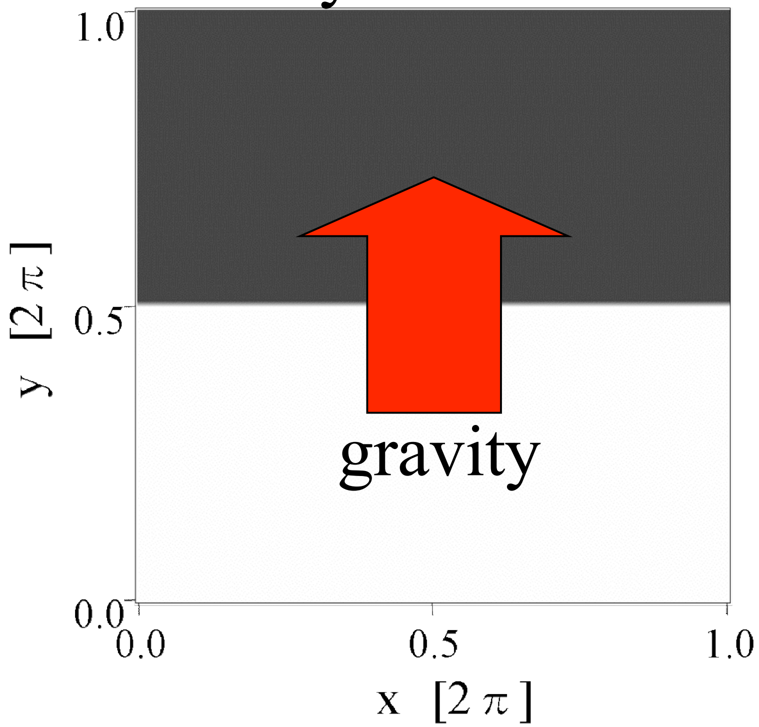
$$\frac{v(f=1[\gamma])}{v(cons\tan t)}\times 100 = 15.40[\%]$$

$$\frac{\omega(f=1[\gamma])}{\omega(cons\tan t)}\times 100 = 55.02[\%]$$

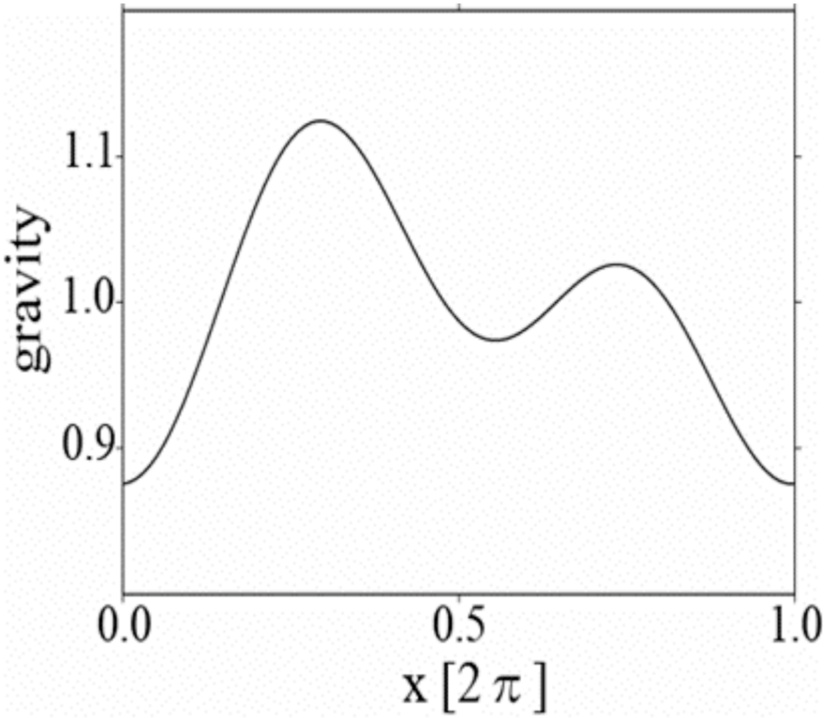
$$\frac{\Delta(f=1[\gamma])}{\Delta(cons\tan t)}\times 100 = 15.58[\%]$$

Multi Mode Simulation [constant gravity]

density



gravity



parameter

$\rho_{High} : 10$

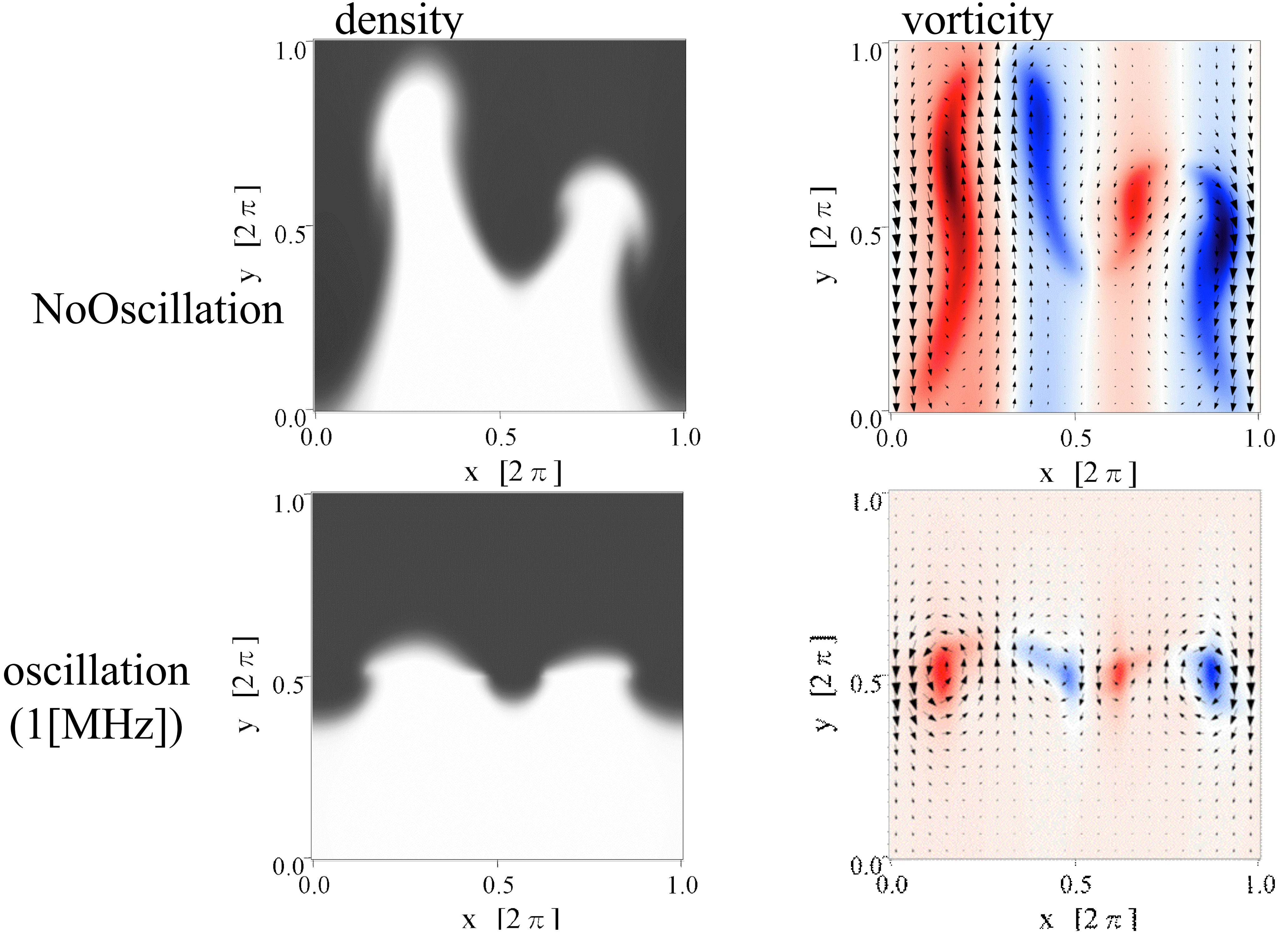
$\rho_{Low} : 3$

$$g : g_0 + \frac{1}{10\sqrt{2}} g_0 \left[\sin(kx) + \sin(2kx) \right]$$

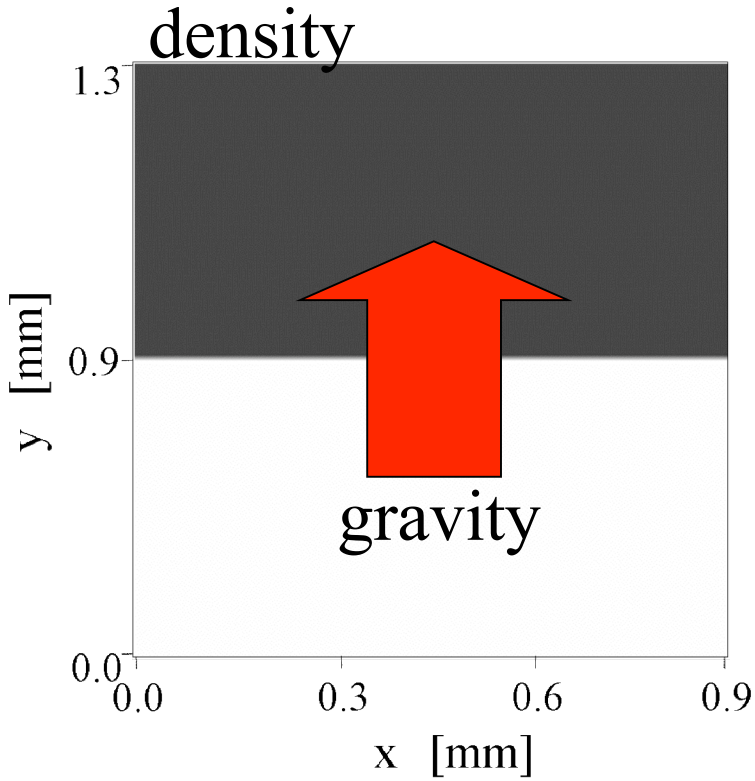
$g_0 : 1$

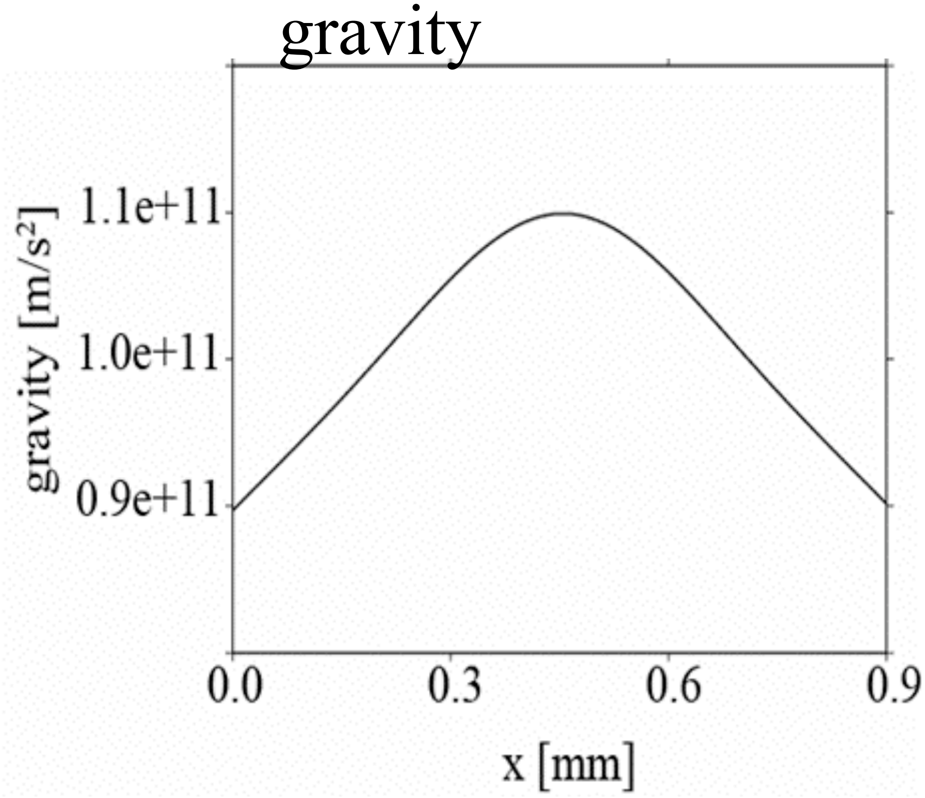
$k : 1$

Multi Mode Comparison (t=5 [1/γ])



Sample (1-beam profile) Simulation [NoOscillation]


density

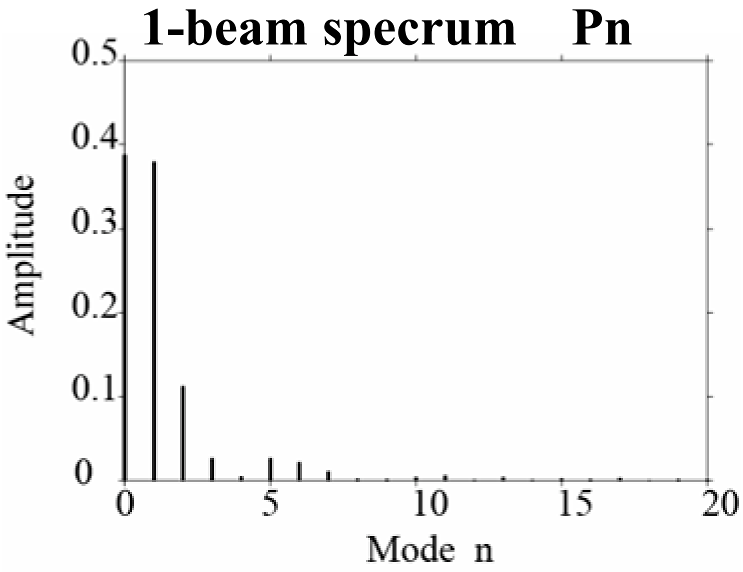

gravity

parameter

$$\rho_{High} : 1000 \left[kg / m^3\right]$$

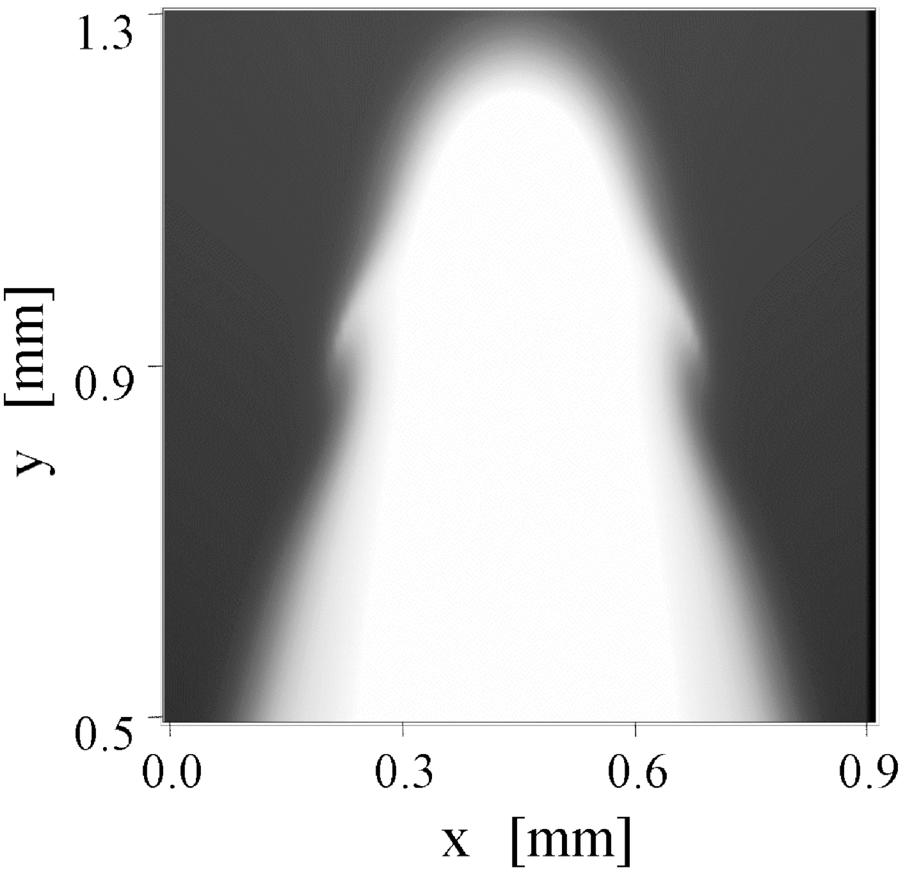
$$\rho_{Low} : 300 \left[kg / m^3\right]$$

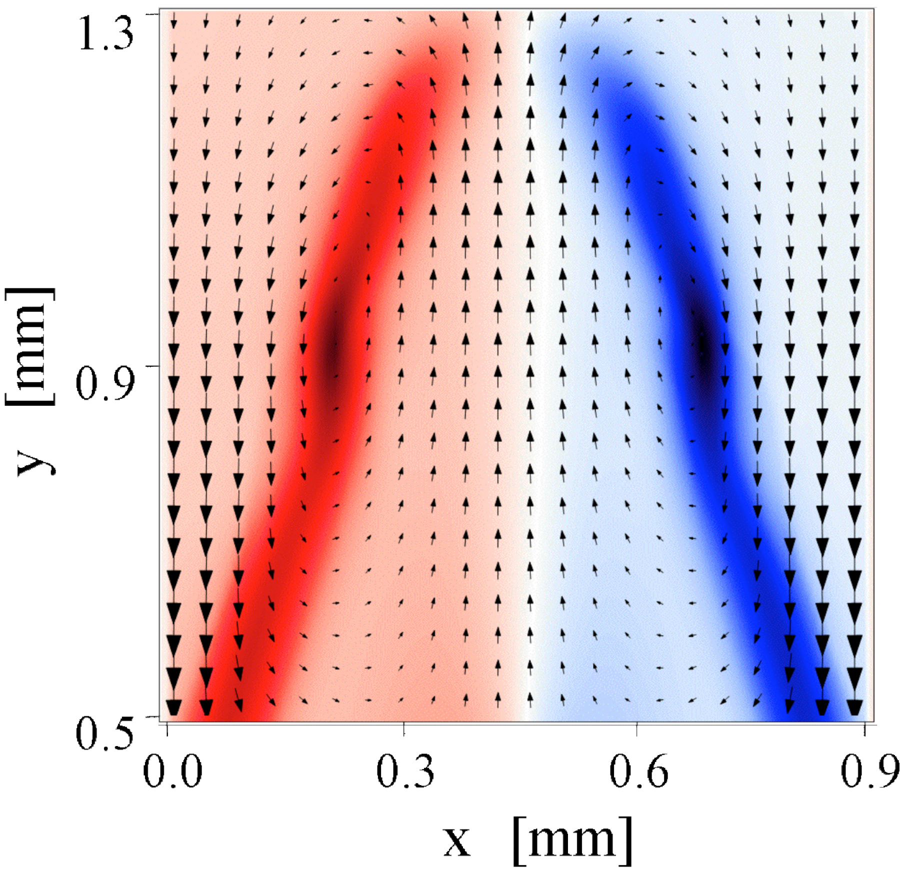
$$g_0 : 10^{11} \left[m / s^2\right]$$


1-beam specrum Pn

Sample (beam profile) Simulation [NoOscillation]

t=0.2 [μ sec]


density


vorticity

Sample Simulation

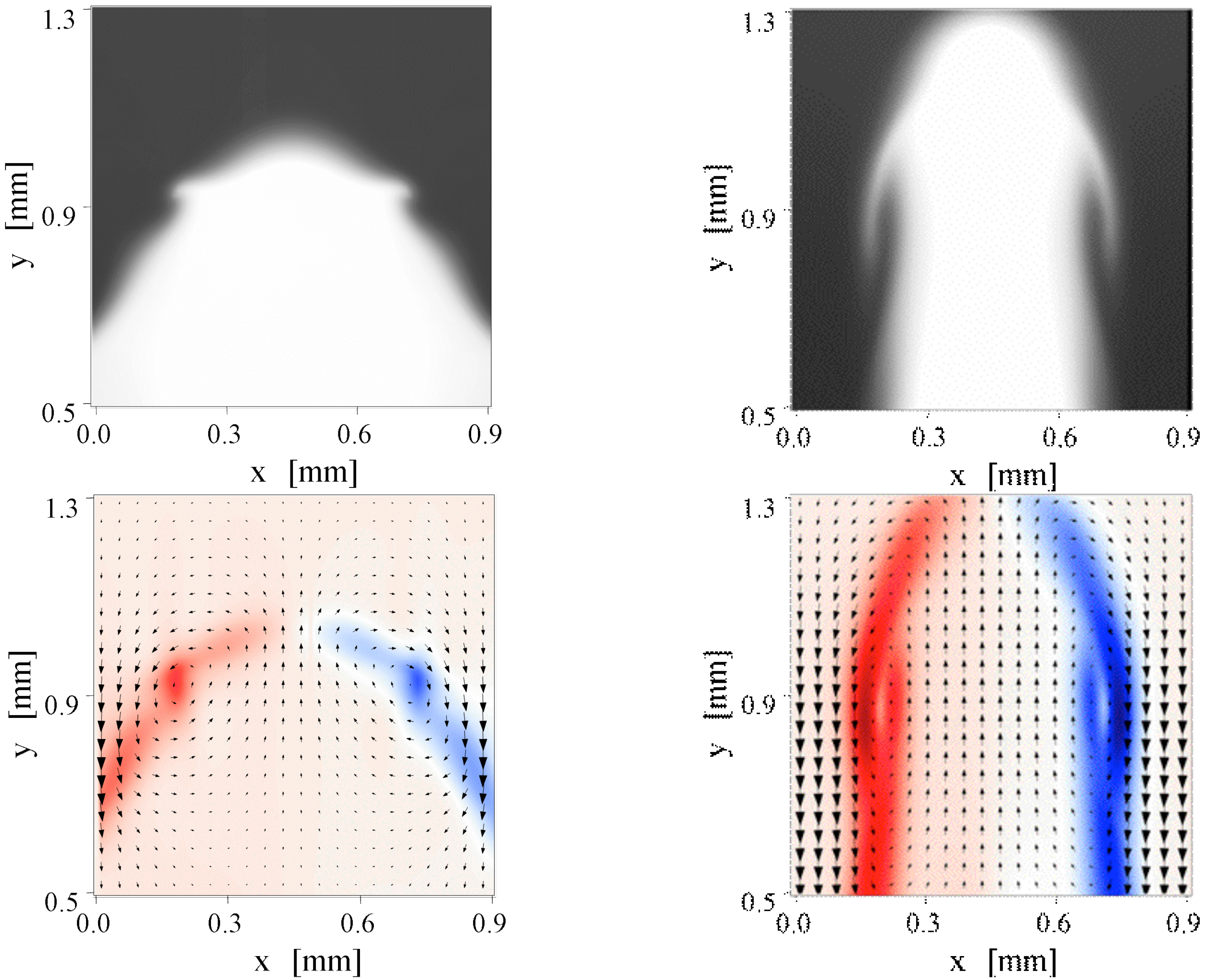
oscillation (10 [MHz])

density

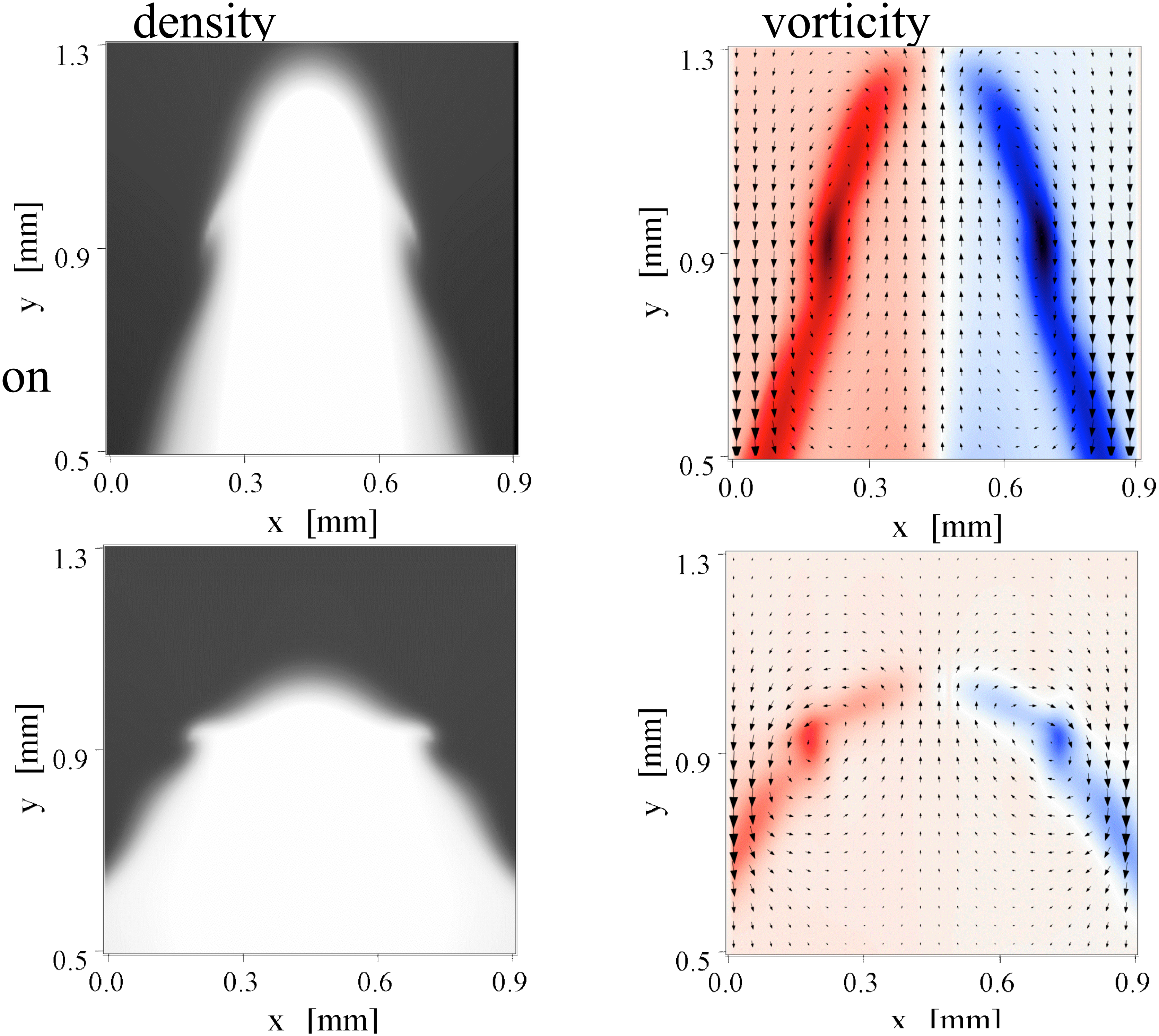
t=0.2 [μ sec]

t=0.3 [μ sec]

vorticity



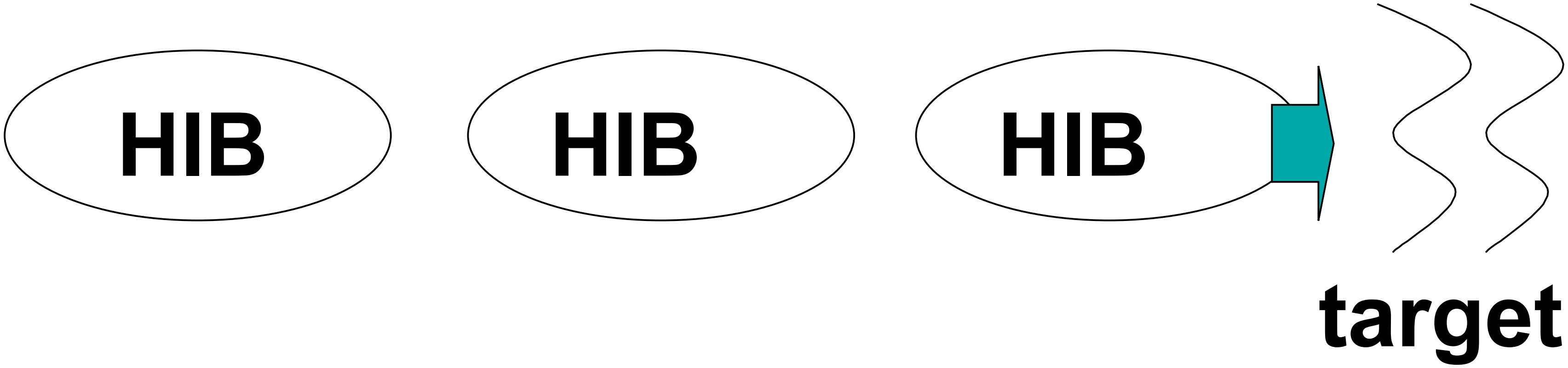
Sample (beam profile) Comparison (t=0.2 [μsec])



NoOscillation

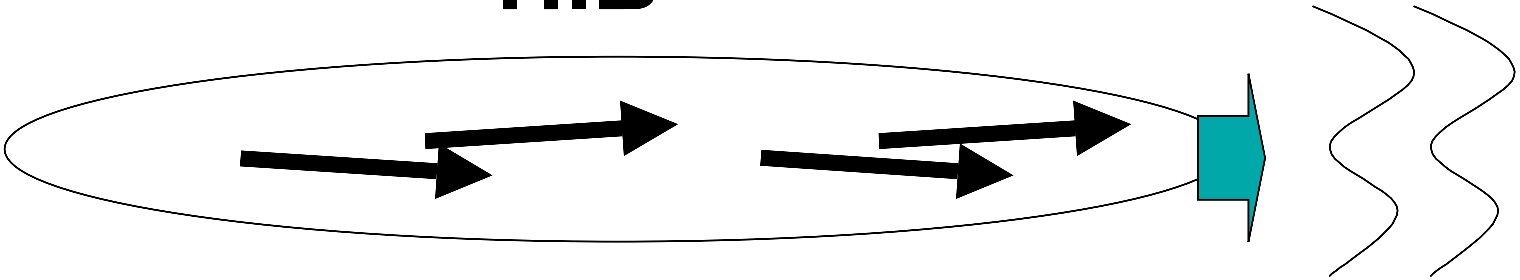
oscillation (10[MHz])

Dynamic R-T Growth Reduction



Successive HIBs induce a dynamically Oscillating *g*!

-> reduce the R-T growth!



HIB

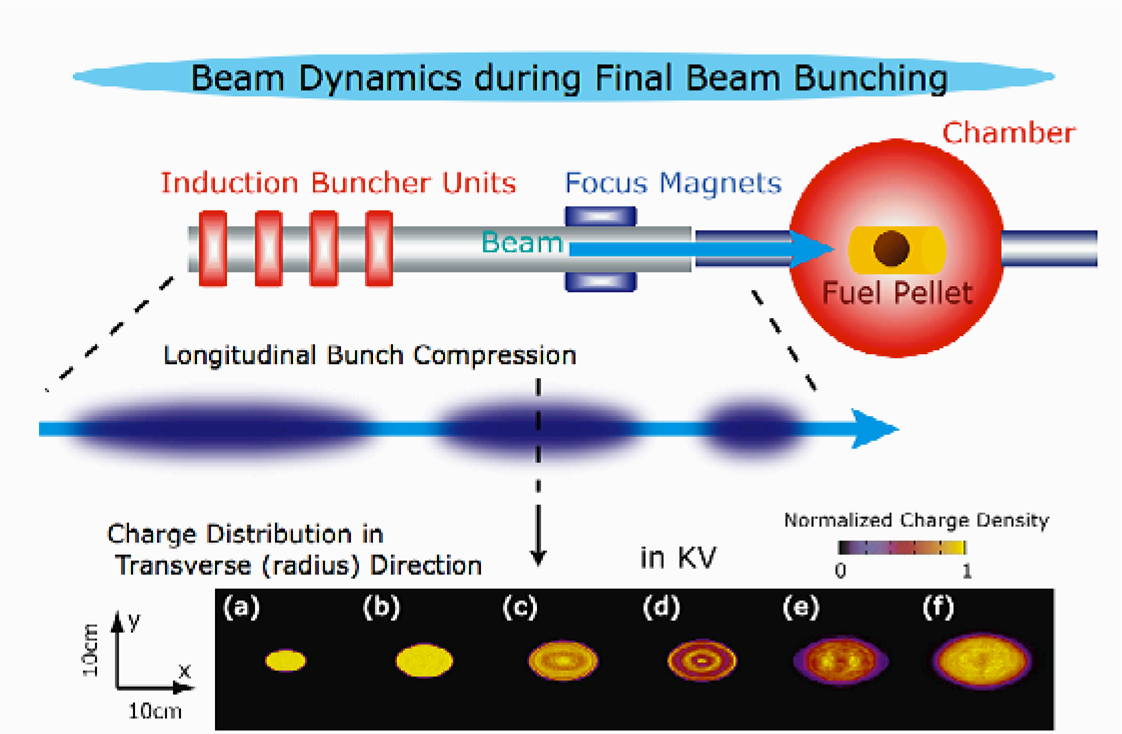
target

HIB axis rotation or swing
-> reduce the R-T growth!

SUMMARY:
HIF Direct-Drive Targets / R-T Instability

S. Kawata, T. Kikuchi
Utsunomiya University

1) Beam Physics _ Final Beam Bunching
2) HIF Implosion & Robust HIB illumination
3) Rayleigh-Taylor Instability Study in HEDP



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