Robust Heavy Ion Fusion Target

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Acknowledgments

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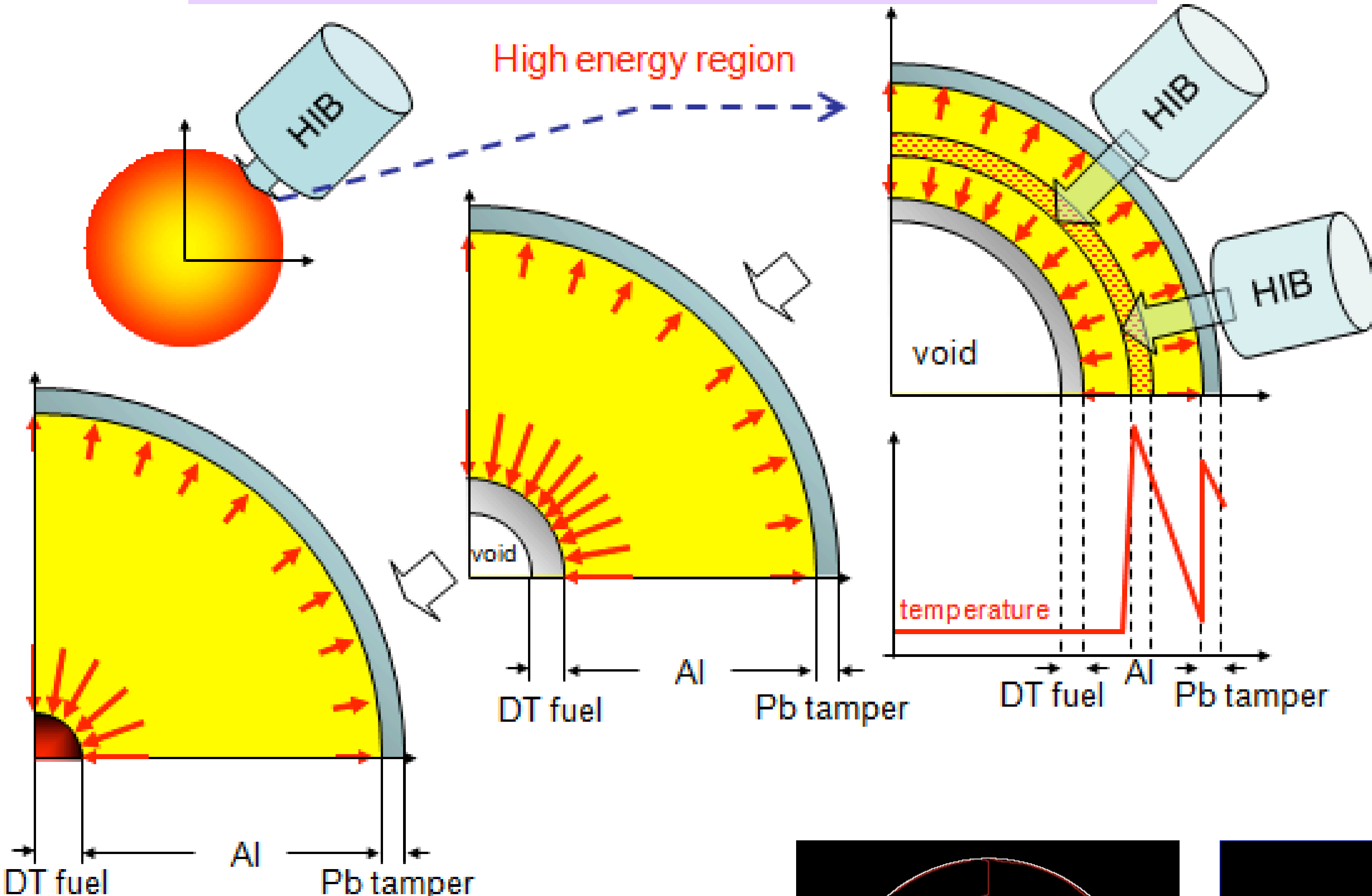
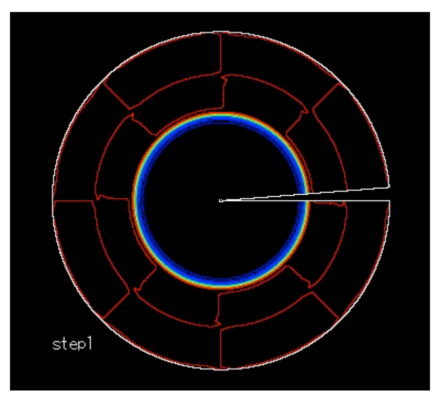
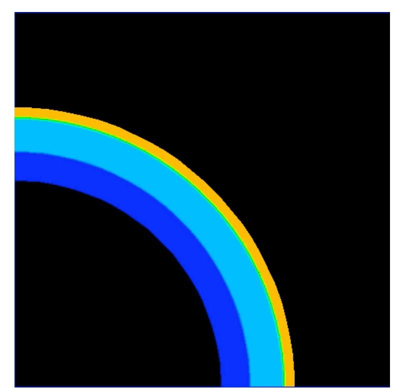
for WDM/HEDM physics + HIF with wobblers!
Colleagues in HIF Japan,
Sasho, Jacob
JSPS & MEXT, Japan

Introduction --- Direct illumination of HIB ---



- / High η_d ~ 30~40%
- / Robust driver with a high rep.
- / Beam handling
- / Spherical target with a hybrid implosion
- / Robust implosion

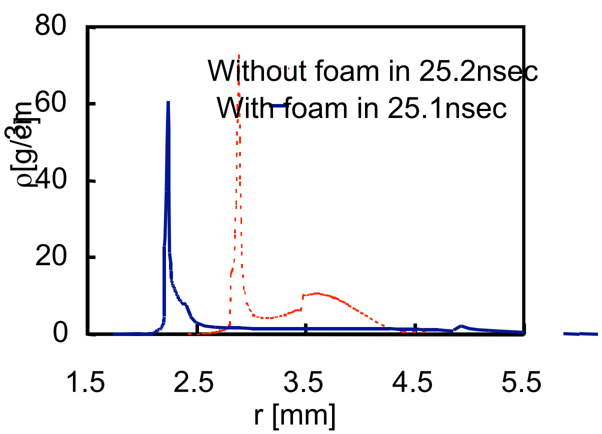




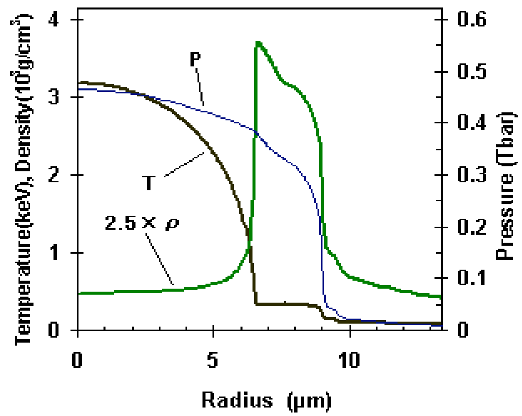
Advantages of HIF Scheme

/ High efficiency ~30~40% => Gain~30 with ~10Hz operation
/ Simple energy deposition
/ Robust against R-T instability <= large density gradient

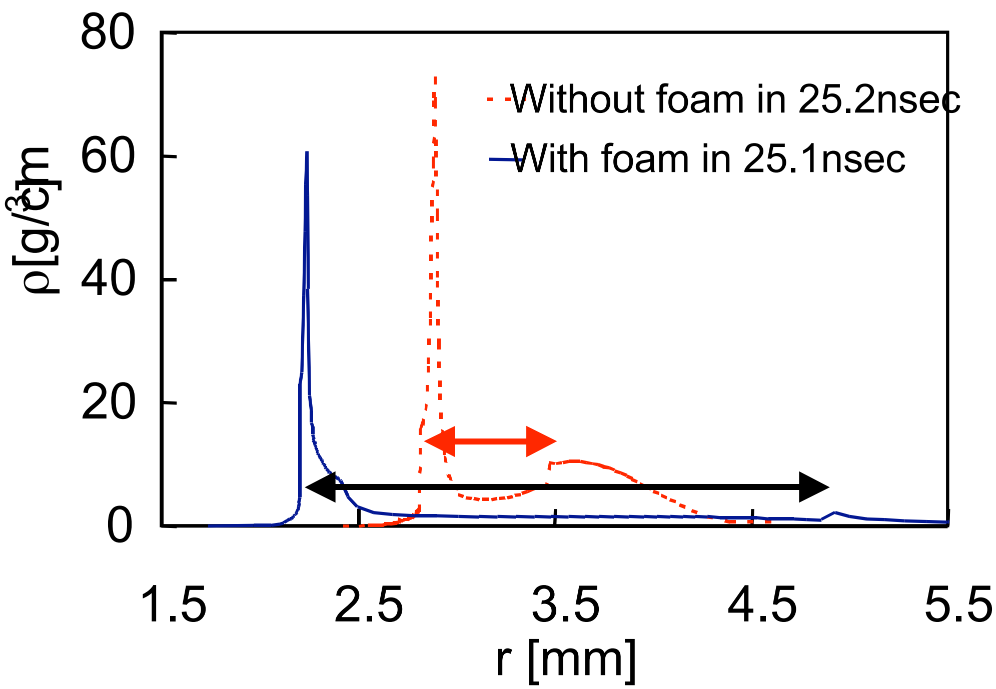
Large scale



Small scale



The Density Valley is Widened by inserting the foam.



Comparison of
space profiles of density

Without foam

Incident beam
: 34 [ns] 7 [MJ]
Nonunifomity
: 2.0 [%]
Maximum incidence angle
: 30 [degree]

With foam

Incident beam
: 34 [ns] 7 [MJ]
Nonunifomity
: 4.0 [%]
Maximum incidence angle
: 40 [degree]

Estimation of the R-T Instability growth

With foam

Incident beam

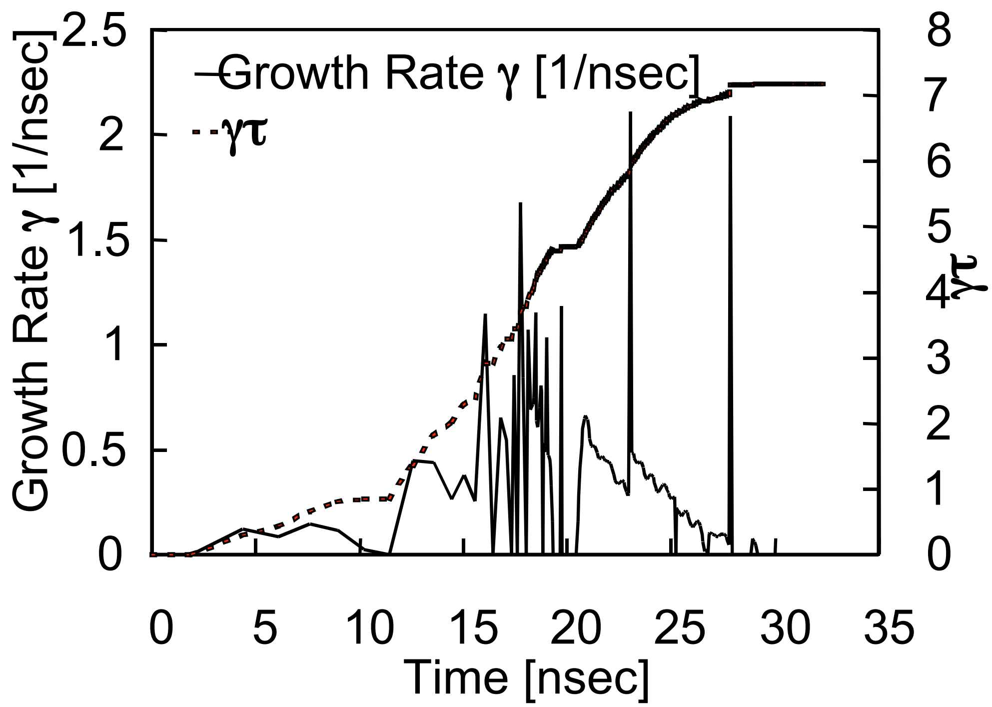
: 34 [ns] 7 [MJ]

Maximum incidence angle

: 40 [degree]

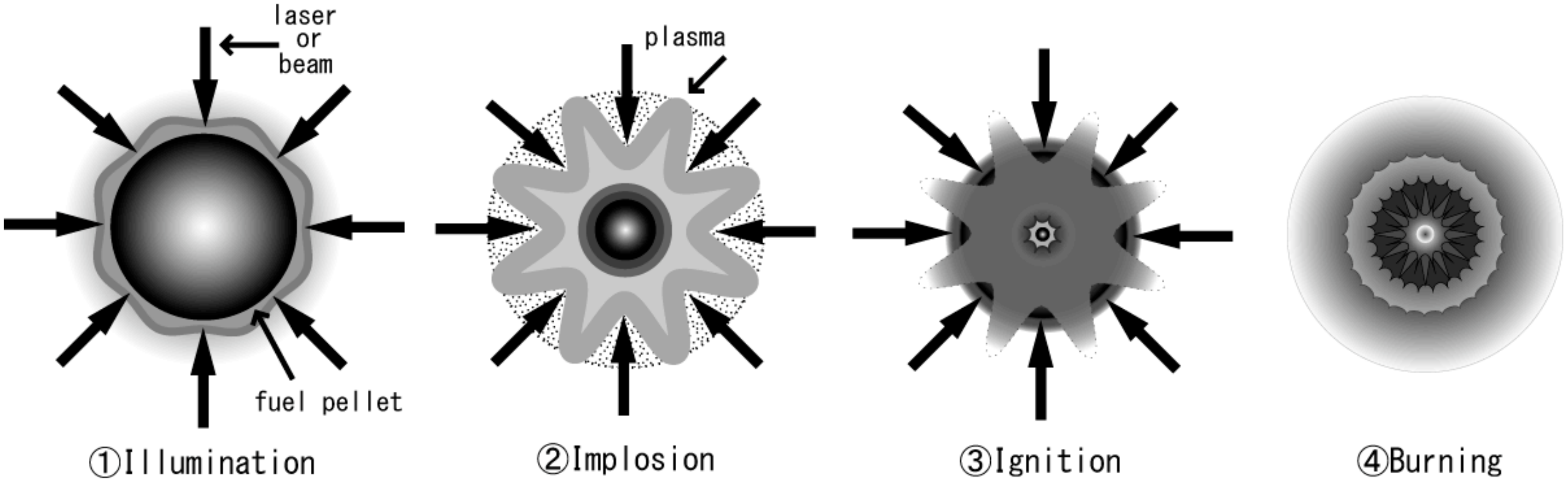
Histories of growth rate of the R-T instability with foam

$$\sqrt{gk}$$



Introduction - Problems of ICF -

Flow of inertial confinement fusion

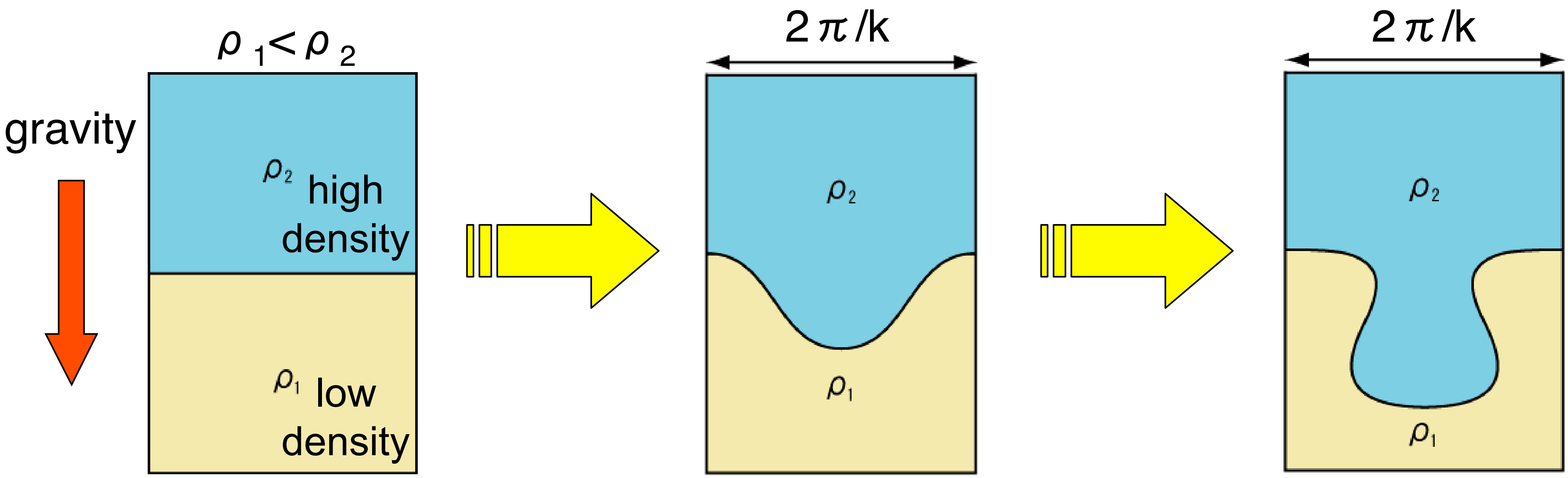


Wobbling HIBs

=> time-dependent energy deposition δE

=> time-dependent non-uniform acceleration: δg

The Rayleigh-Taylor Instability (RTI)



- When a low density fluid supports a high density one under gravity, the fluid instability is caused.
- This instability is so called the Rayleigh-Taylor Instability (RTI).

- The growth rate of the RTI is

$$\gamma = \sqrt{gk\frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}}$$

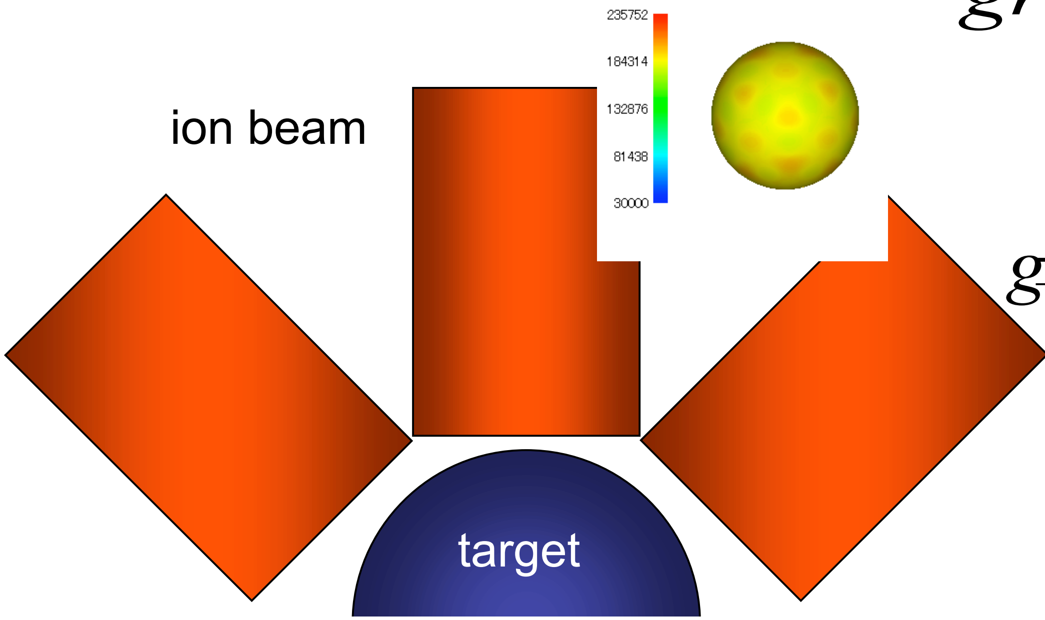
γ : *growth rate*

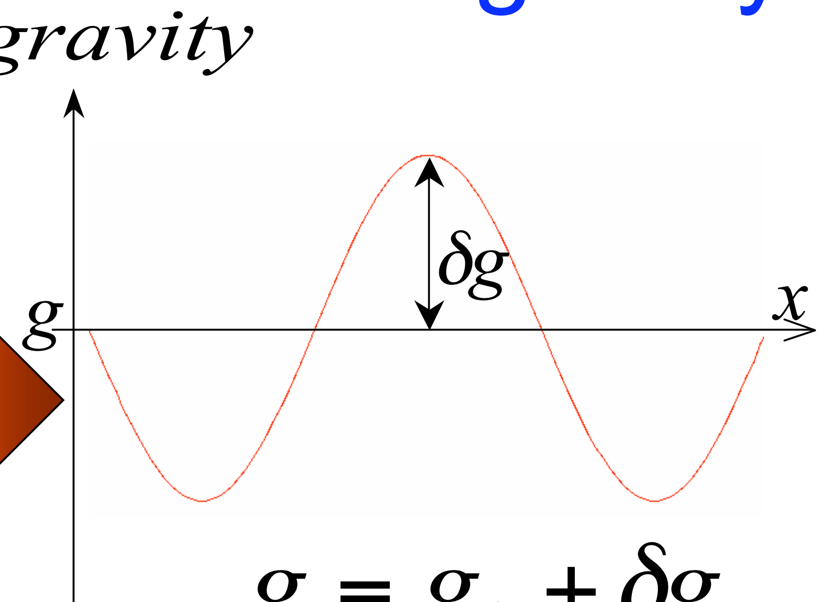
g : *gravity*

k : *wave namber*

ρ : *density*

RTI induced by non-uniform gravity





$$g = g_0 + \delta g$$

g_0 : constant gravity

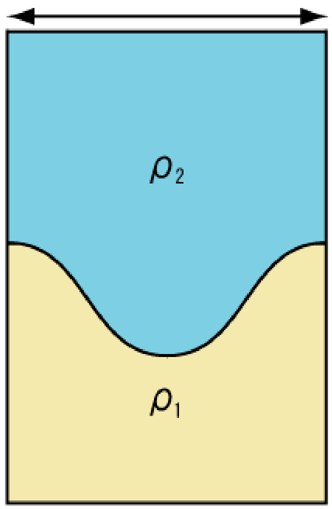
δg : non-uniform gravity

A non-uniform acceleration (gravity) is generated by non-uniform illumination of heavy ion beams.

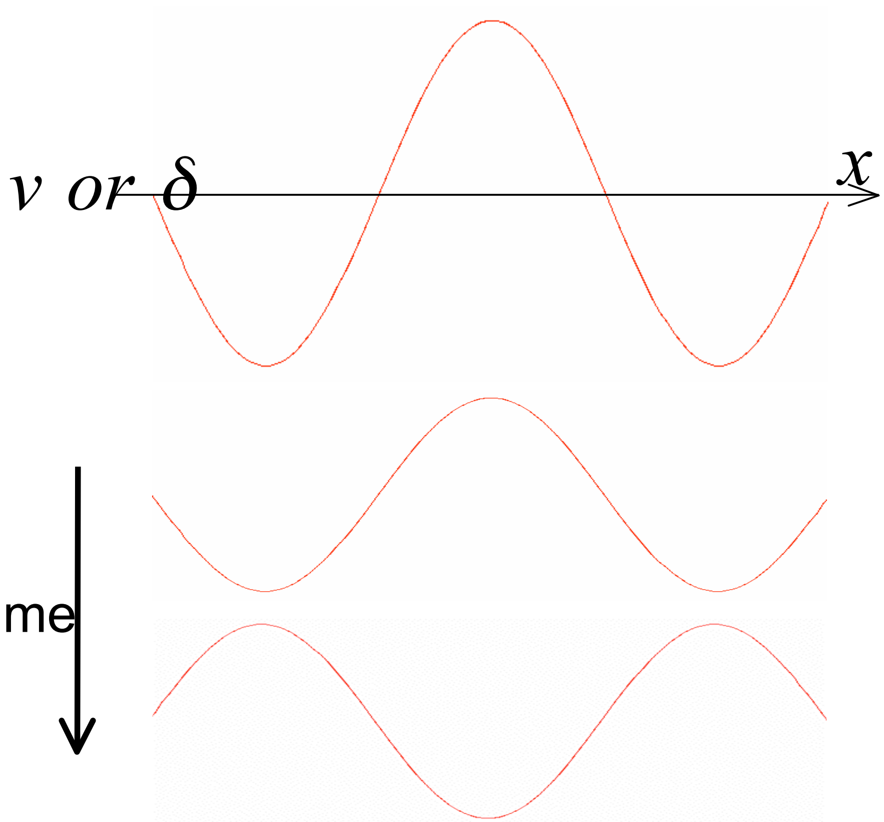
Because the beam number is finite.

The gravity is expressed by the constant term and the non-uniform term, in this study.

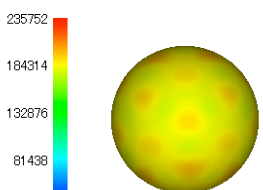
RTI induced by non-uniform gravity



$$g = g_0 + \delta g$$

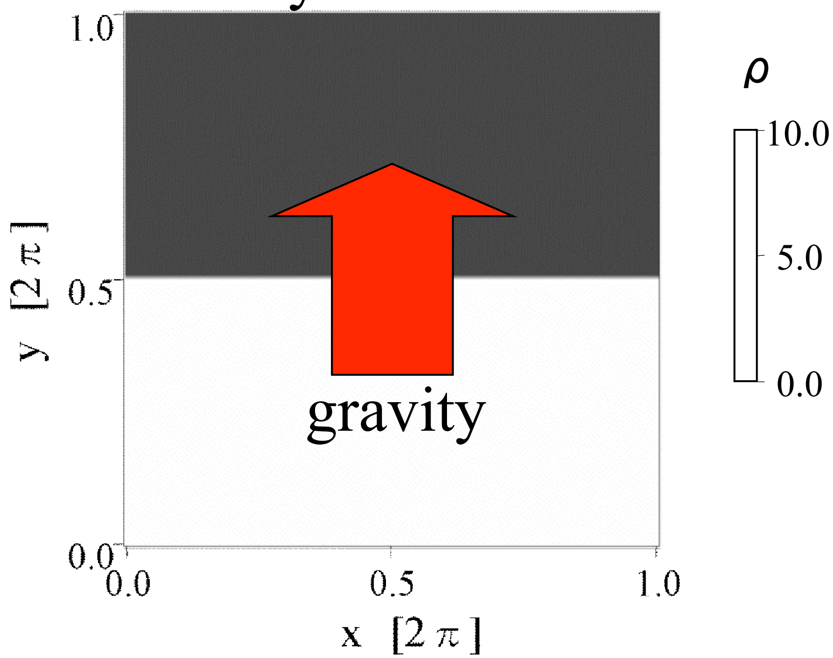


δg

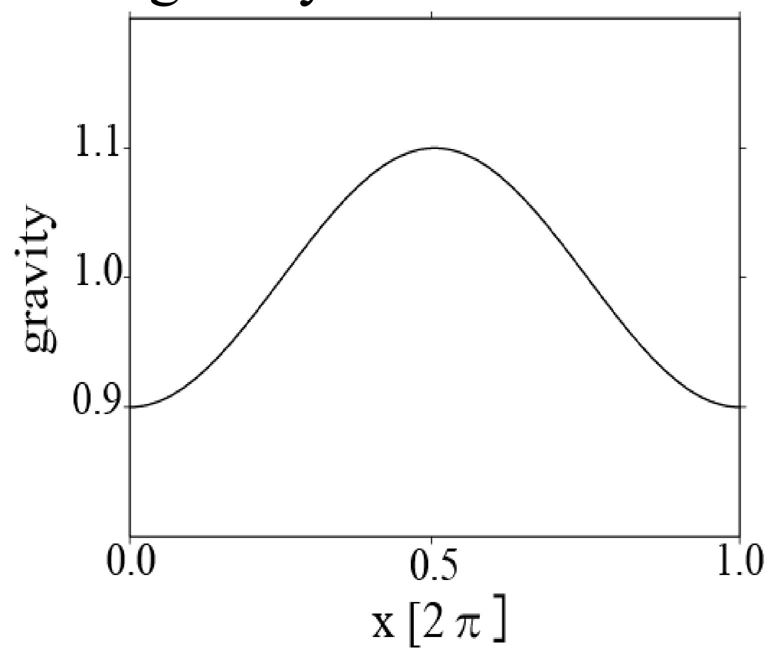


Simulation model - constant gravity -

density



gravity



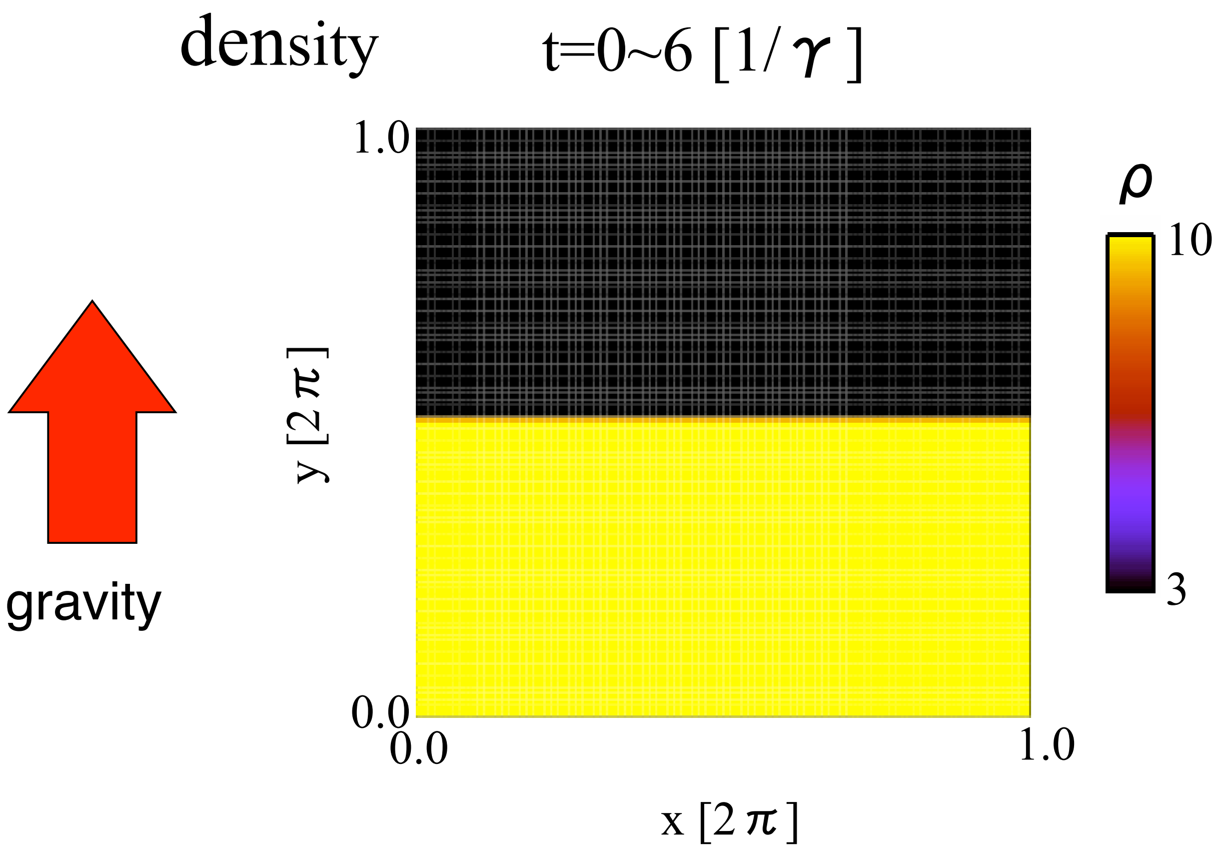
The calculation parameters are

$\rho_{High} : 10$ $\quad g_0 : 1$

$\rho_{Low} : 3$ $\quad k : 1$

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

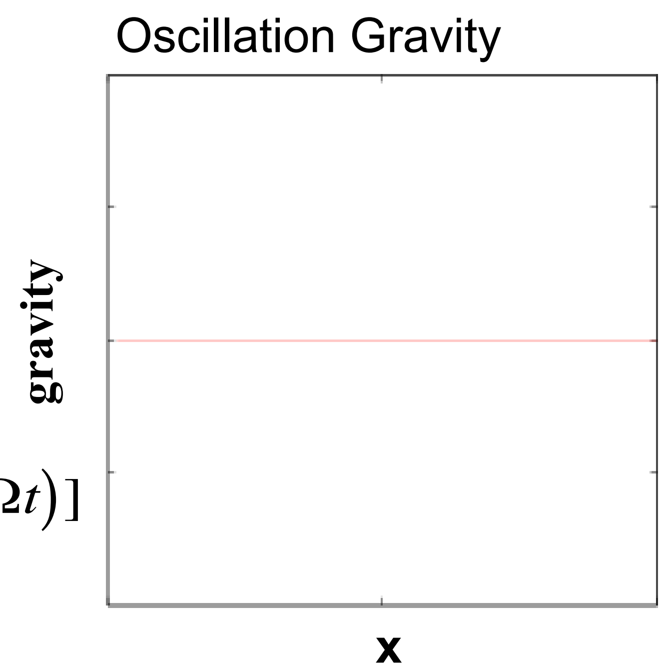
Simulation result - constant gravity -



- The RTI is grown by the initial unstable density and the non-uniform gravity distributions.

HIB axis can be oscillated with a high frequency -> Control of RTI - Oscillating gravity -

$$g(x,y,z,t) = g_0 + \delta g(x,y,z,t)$$
$$= g_0 + g_1 f_1(x,y)\exp\left(-\beta|z|\right)\exp\left(i\Omega t\right)$$



$$w_0 \propto \delta g \Delta t$$
$$\Omega = 2\pi f$$

$$w = \frac{\gamma + i\Omega}{\gamma^2 + \Omega^2} g_1 \exp(ik_x + ik_y)[\exp(\gamma t) - \exp(i\Omega t)]$$

From the equation, when the gravity oscillation frequency *f* increases, the RTI perturbation velocity *w* decreases.

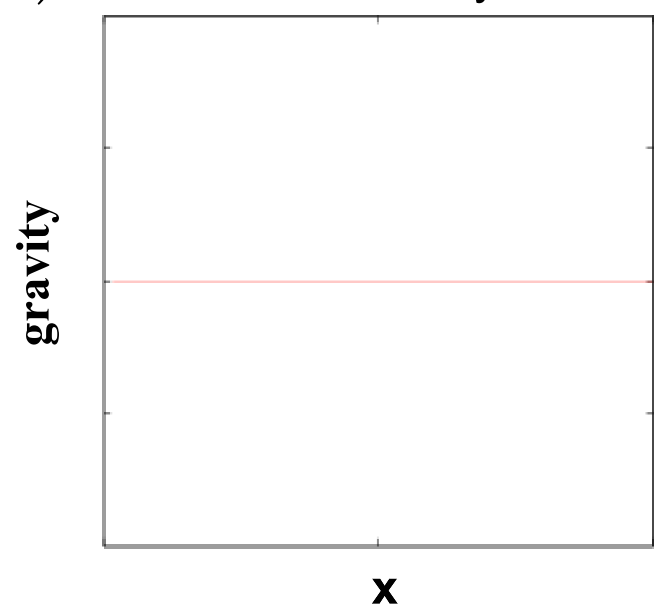
w : *velocity* $\quad \gamma$: *growth rate* $\quad f$: *frequency*

w_0 : *initial velocity* $\quad \delta g$: *non-uniform gravity* $\quad t$: *time*

Control of RTI - Oscillating gravity -

$$w = \frac{\gamma + i\Omega}{\gamma^2 + \Omega^2} g_1 \exp(ik_x + ik_y)[\exp(\gamma t) - \exp(i\Omega t)]$$

Oscillation Gravity



$$|w| \approx \frac{1}{\Omega} g_1 \exp(\gamma t) \quad for\ \gamma << \Omega$$

$$|w| \approx \frac{1}{2\gamma} g_1 \exp(\gamma t) \quad for\ \gamma = \Omega$$

The RTI perturbation velocity is approximately written by <-.

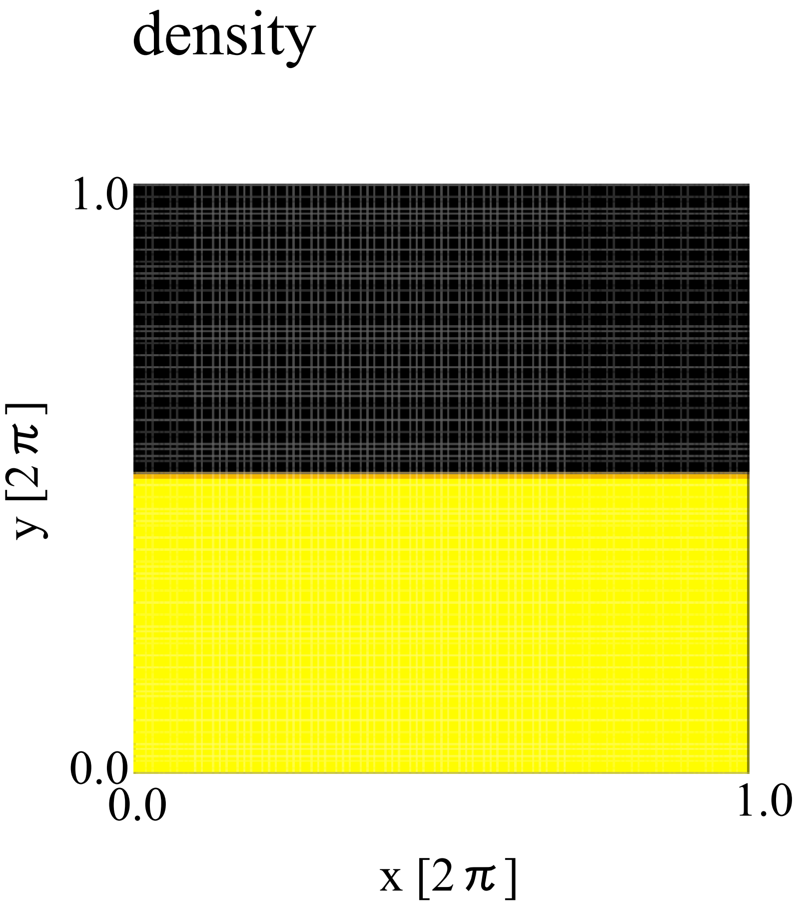
$w : velocity \quad \gamma : growth\ rate \quad f : frequency$

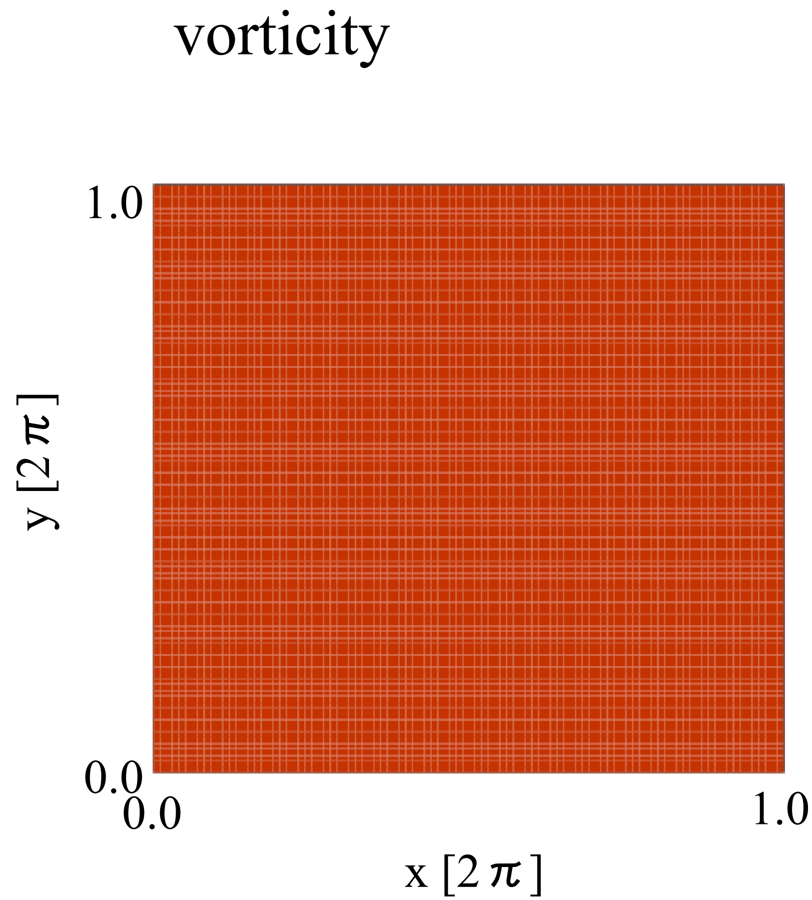
$w_0 : initial\ velocity \quad \delta g : non-uniform\ gravity \quad t : time$

From the equation, when the gravity oscillation frequency *f* is increased, the RTI perturbation velocity *w* decreases.

Single Mode Simulation [constant gravity]

t=0~6 [1/ γ]



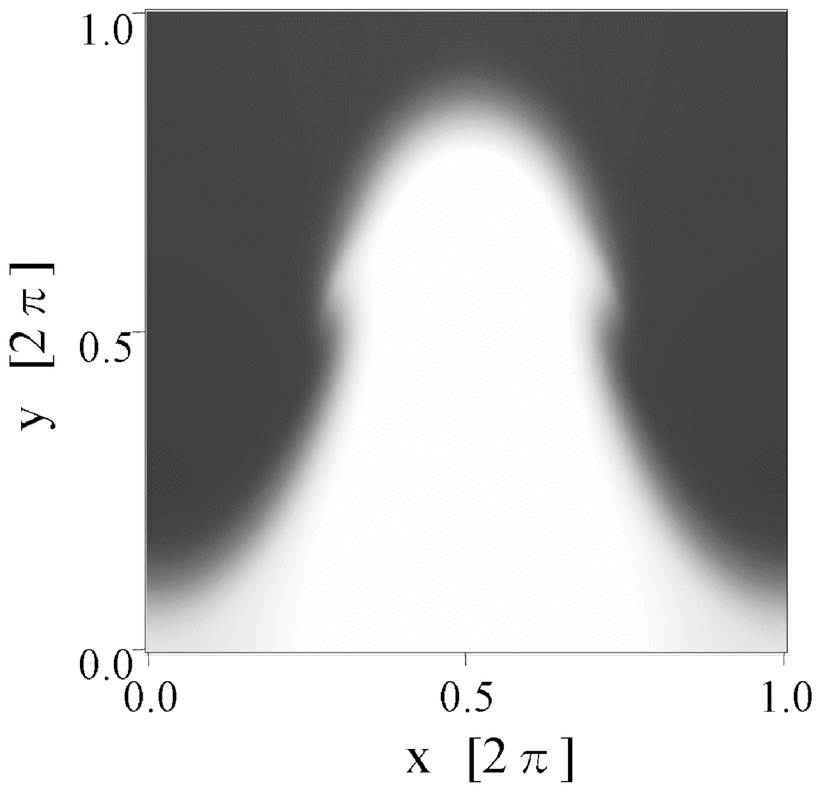


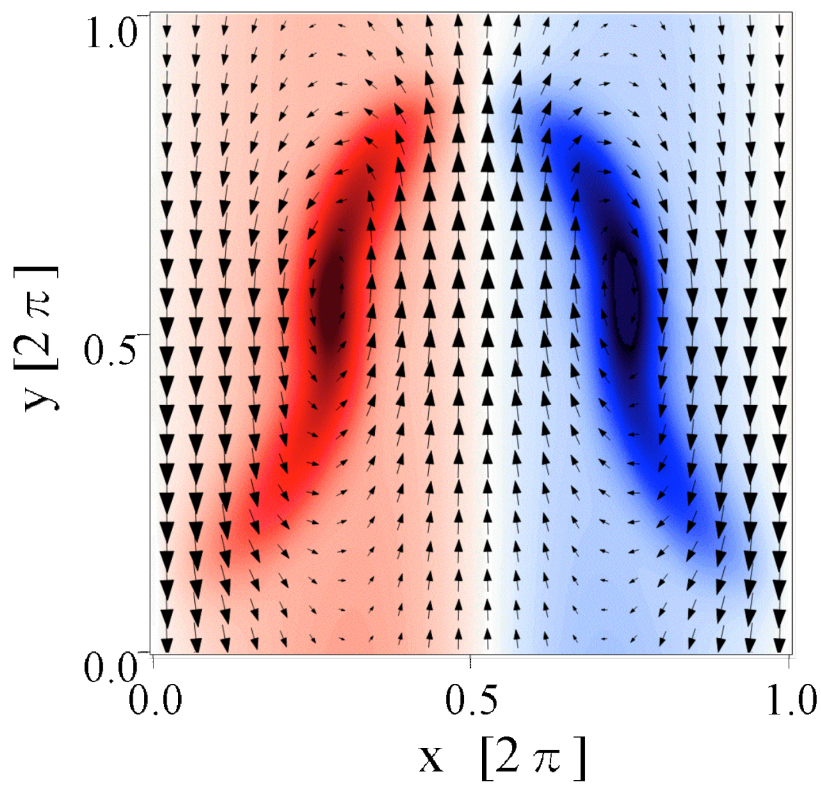
Single Mode Simulation [constant gravity]

t=5 [1/ γ]

density

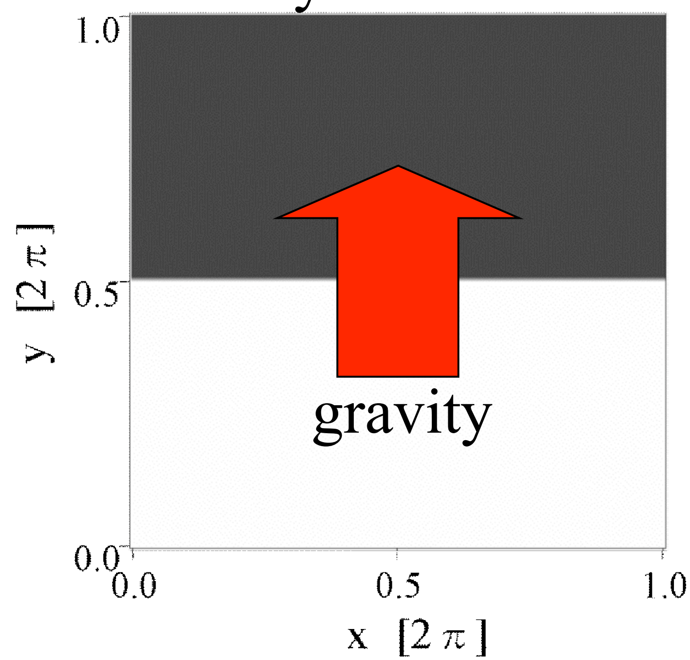
vorticity



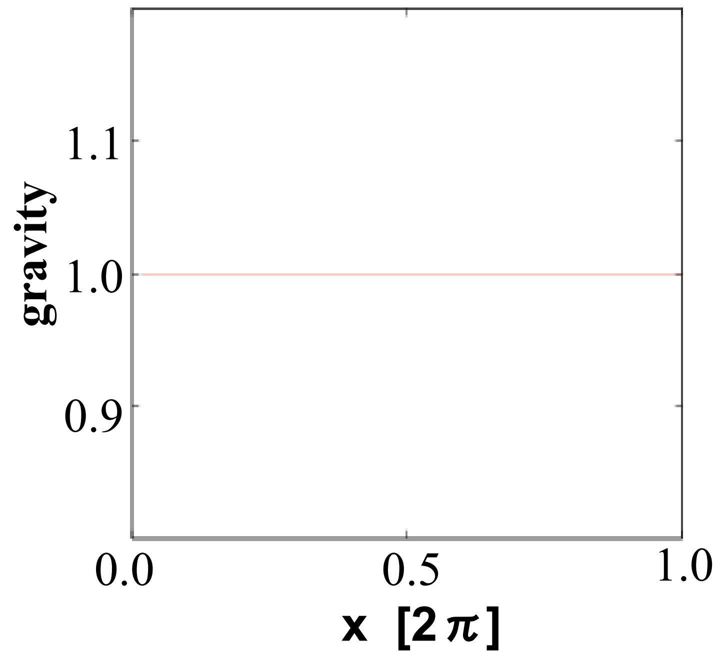


Single Mode Simulation [oscillation gravity]

density



gravity

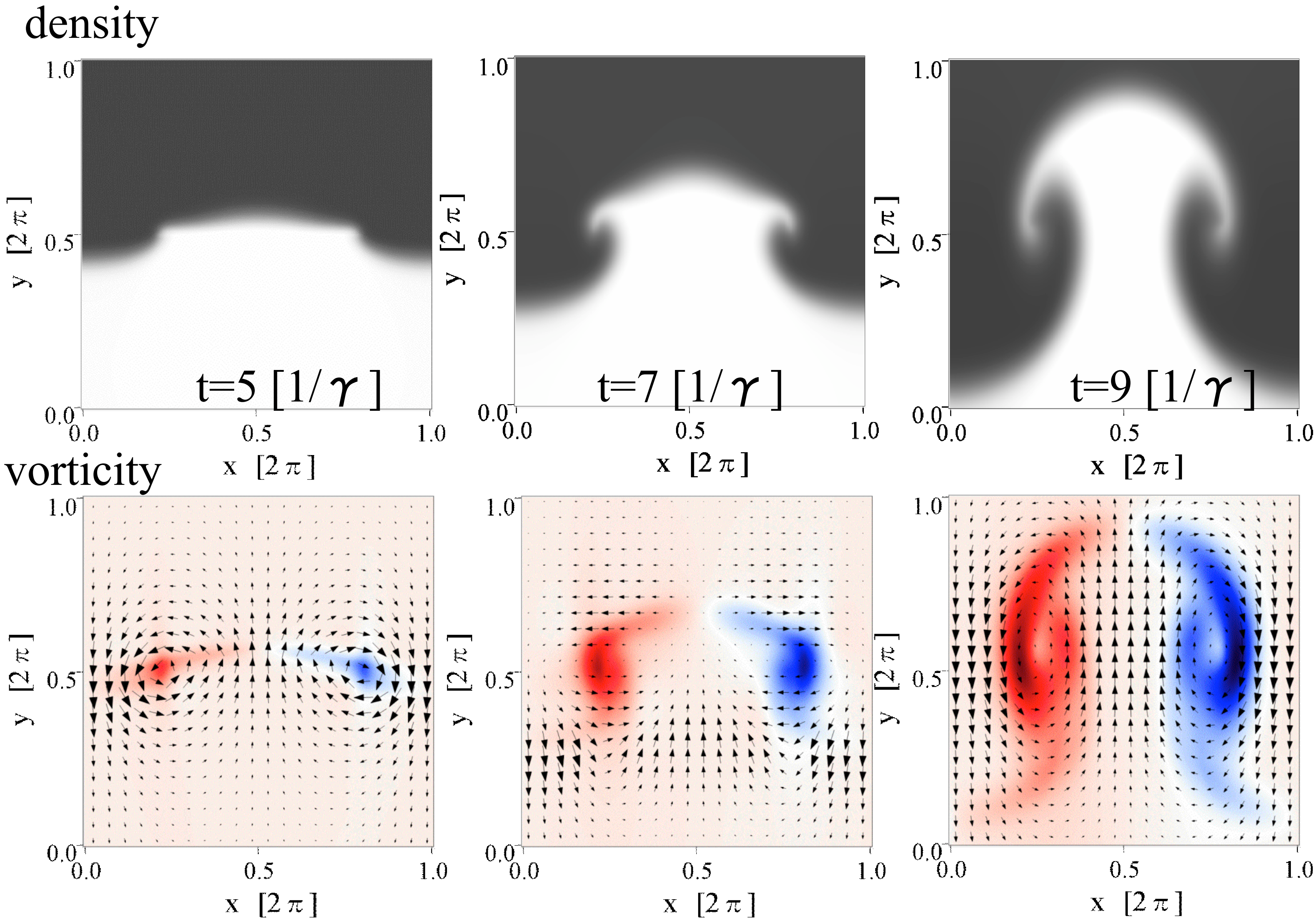


parameter

ρ_{High} : 10	g_0 : 1
ρ_{Low} : 3	k : 1
$g : g_0 + 0.1 g_0 \sin(kx)\sin(2\pi f t)$	$f : \gamma \quad \left(\gamma = \sqrt{g_0 k}\right)$

$$ex.\ g_0 = 10^{15}\left[m/s^2\right], k = 1\left[1/mm\right] \rightarrow f = 10^9\left[Hz\right]$$

Single Mode Simulation oscillation (γ [Hz])

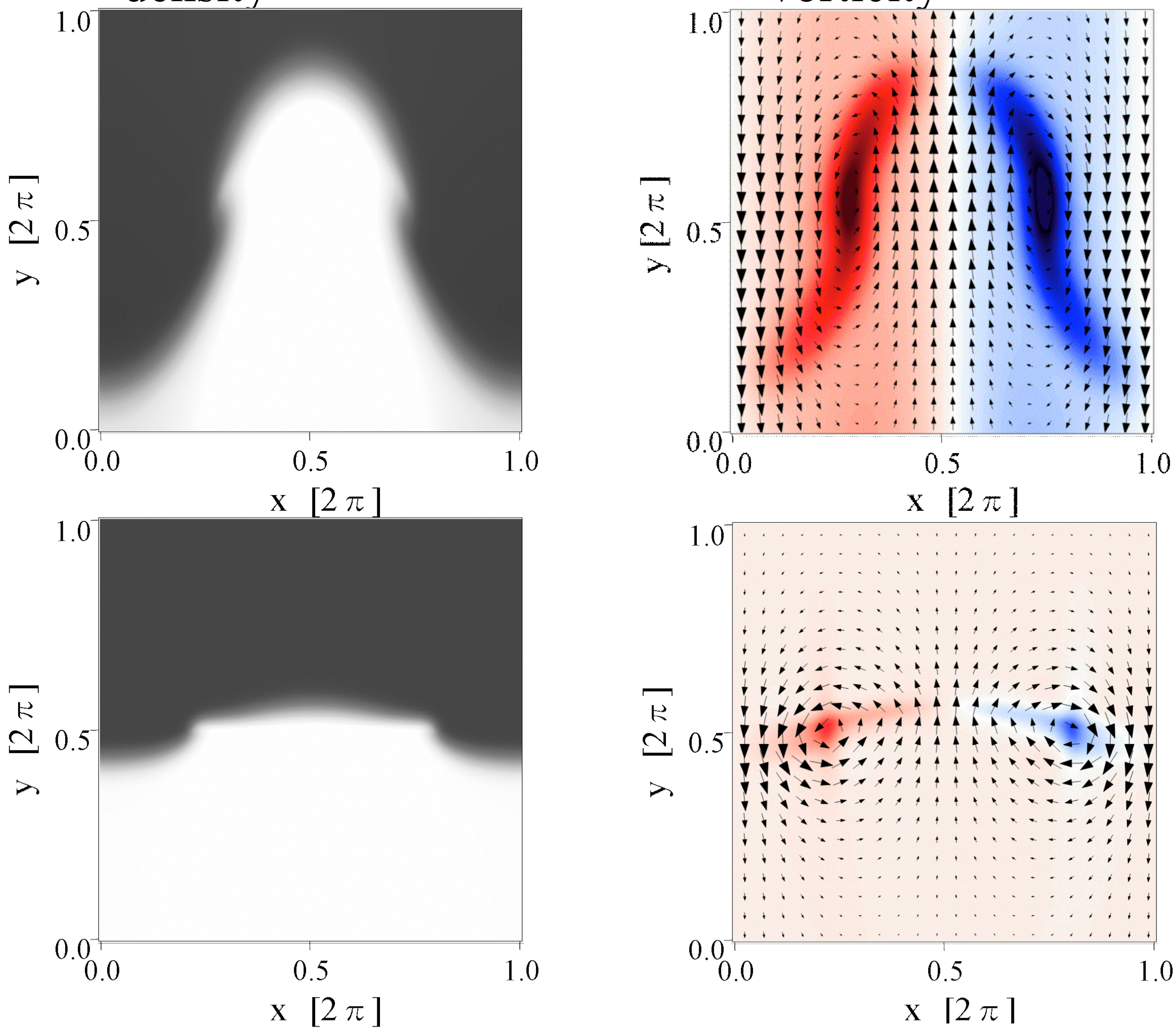


Single Mode Comparison (γt=5)

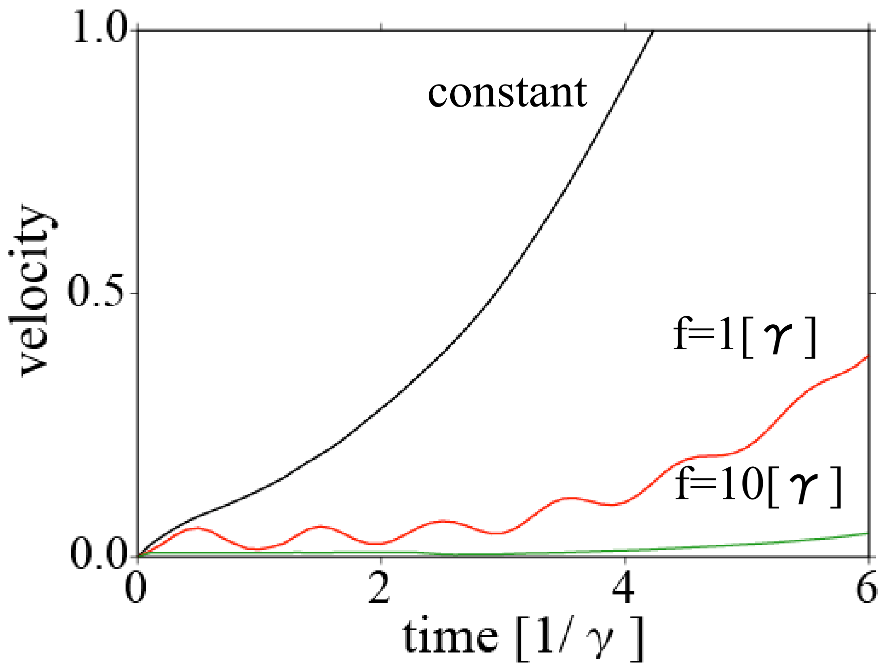
density vorticity

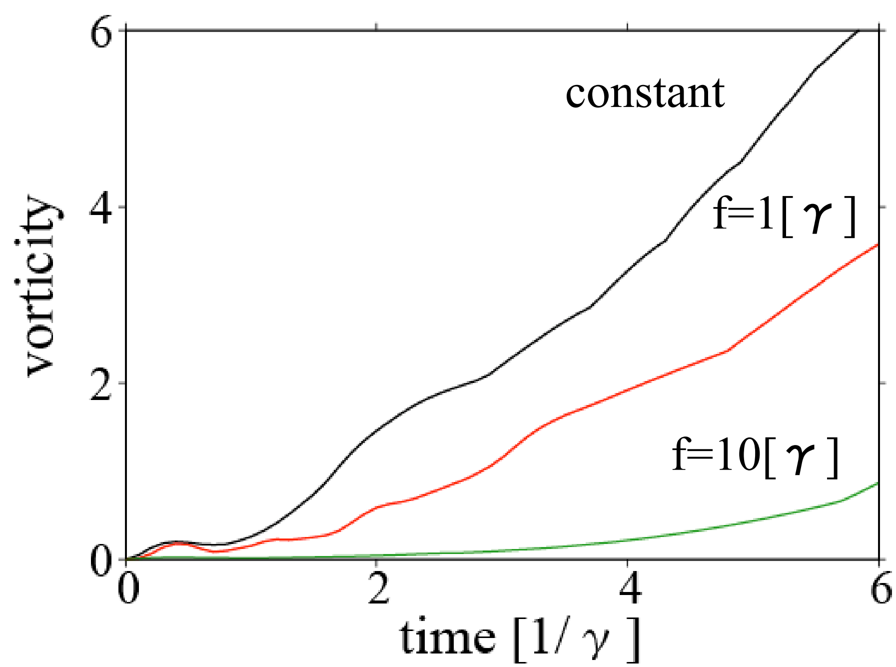
constant

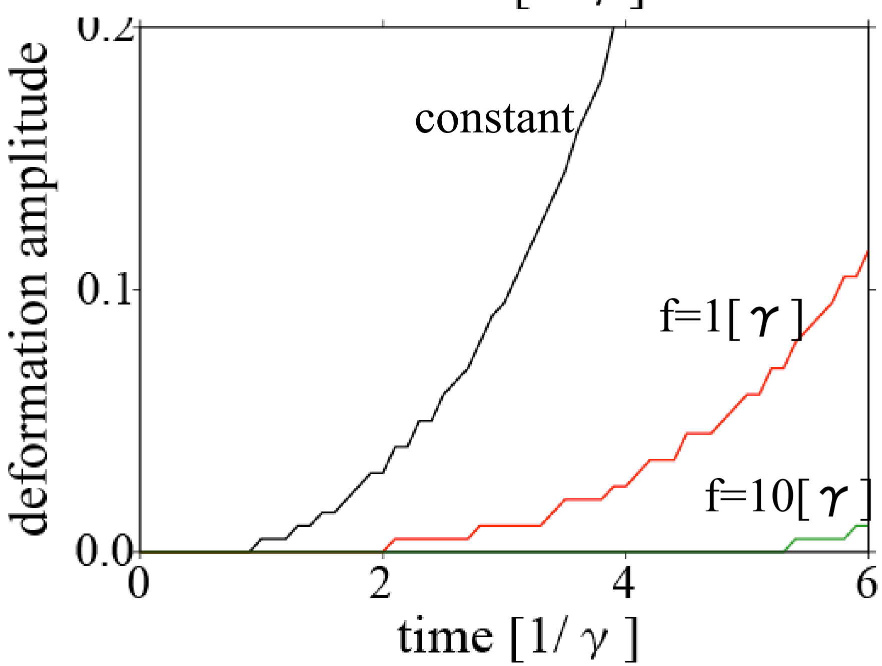
oscillation
(γ [Hz])



Single Mode Comparison (passage of time)







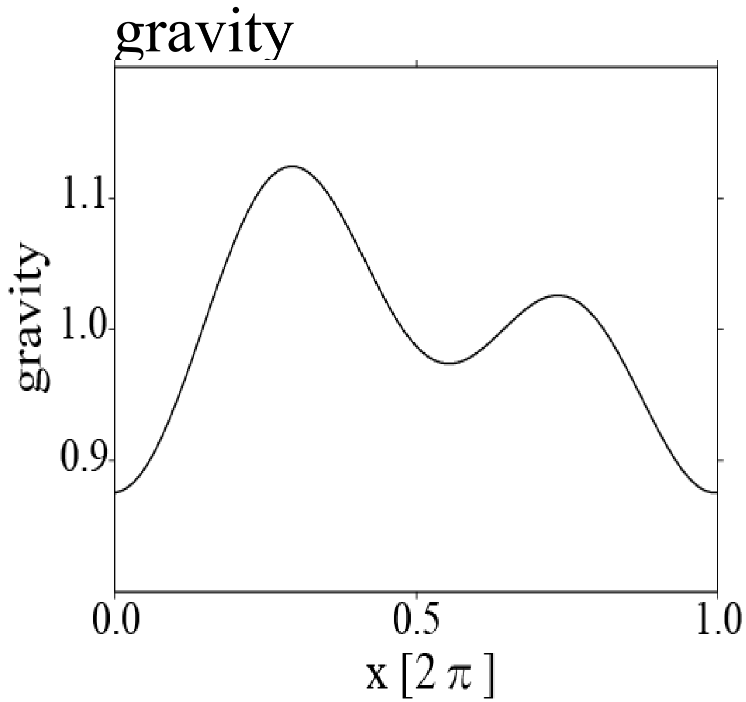
$time[1/\gamma]: 5$

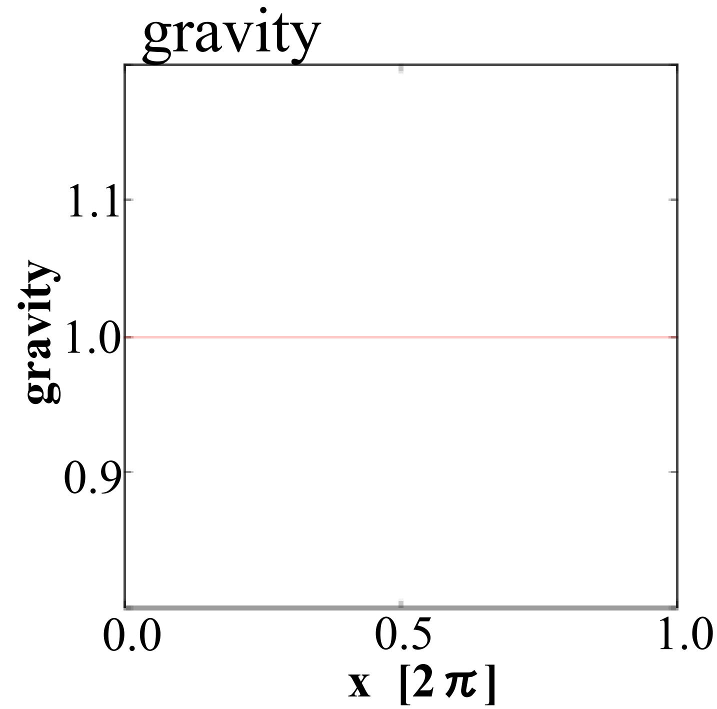
$$\frac{v(f=1[\gamma])}{v(\mathit{constant})}\times 100 = 15.40[\%]$$

$$\frac{\omega(f=1[\gamma])}{\omega(\mathit{constant})}\times 100 = 55.02[\%]$$

$$\frac{\Delta(f=1[\gamma])}{\Delta(\mathit{constant})}\times 100 = 15.58[\%]$$

Multi Mode Simulation [oscillation gravity]





parameter

ρ_{High} : 10

ρ_{Low} : 3

$g : g_0 + \frac{1}{10\sqrt{2}} g_0 [\sin(kx) + \sin(ckx)] \sin(2\pi f t)$

g_0 : 1

k : 1

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

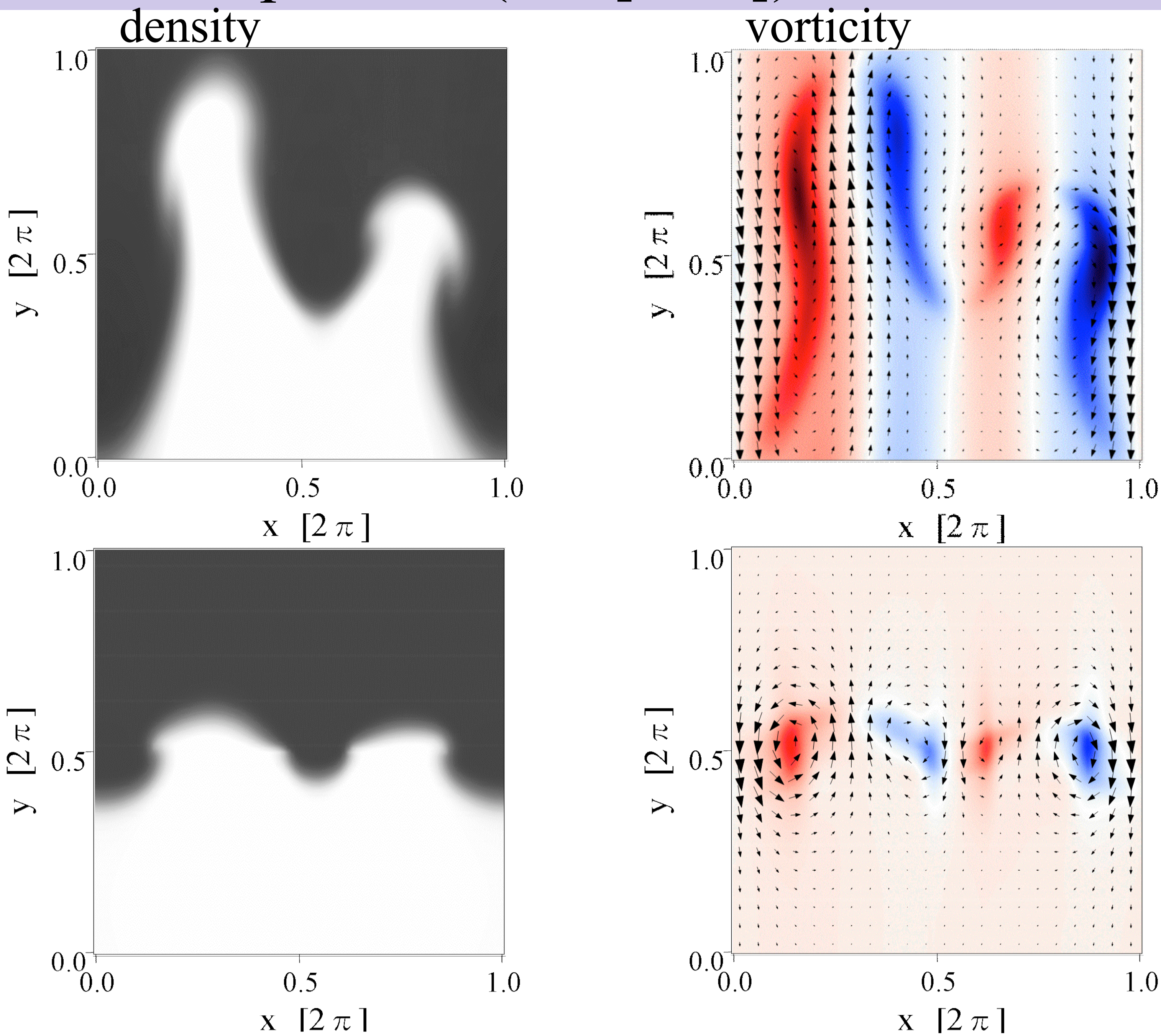
$$ex.\ g_0 = 10^9 [m/s]\ k = 1 [1/mm] \rightarrow f = 10^6 [Hz]$$

Multi Mode Comparison (t=5 [1/γ])

constant

oscillation

(γ [Hz])



Illumination of Wobblers

Parameters

Pb^{+} ion beam

Beam number : 12, 32

Beam particle energy : 8GeV

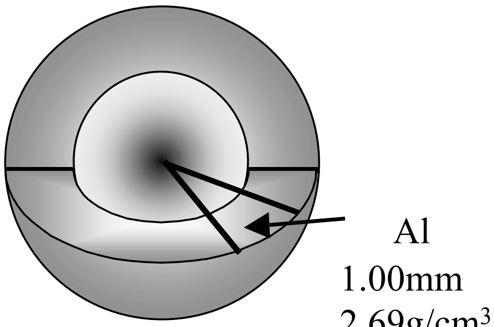
Beam particle density distribution : Gaussian

Beam temperature of projectile ions : 100MeV with the Maxwell distribution

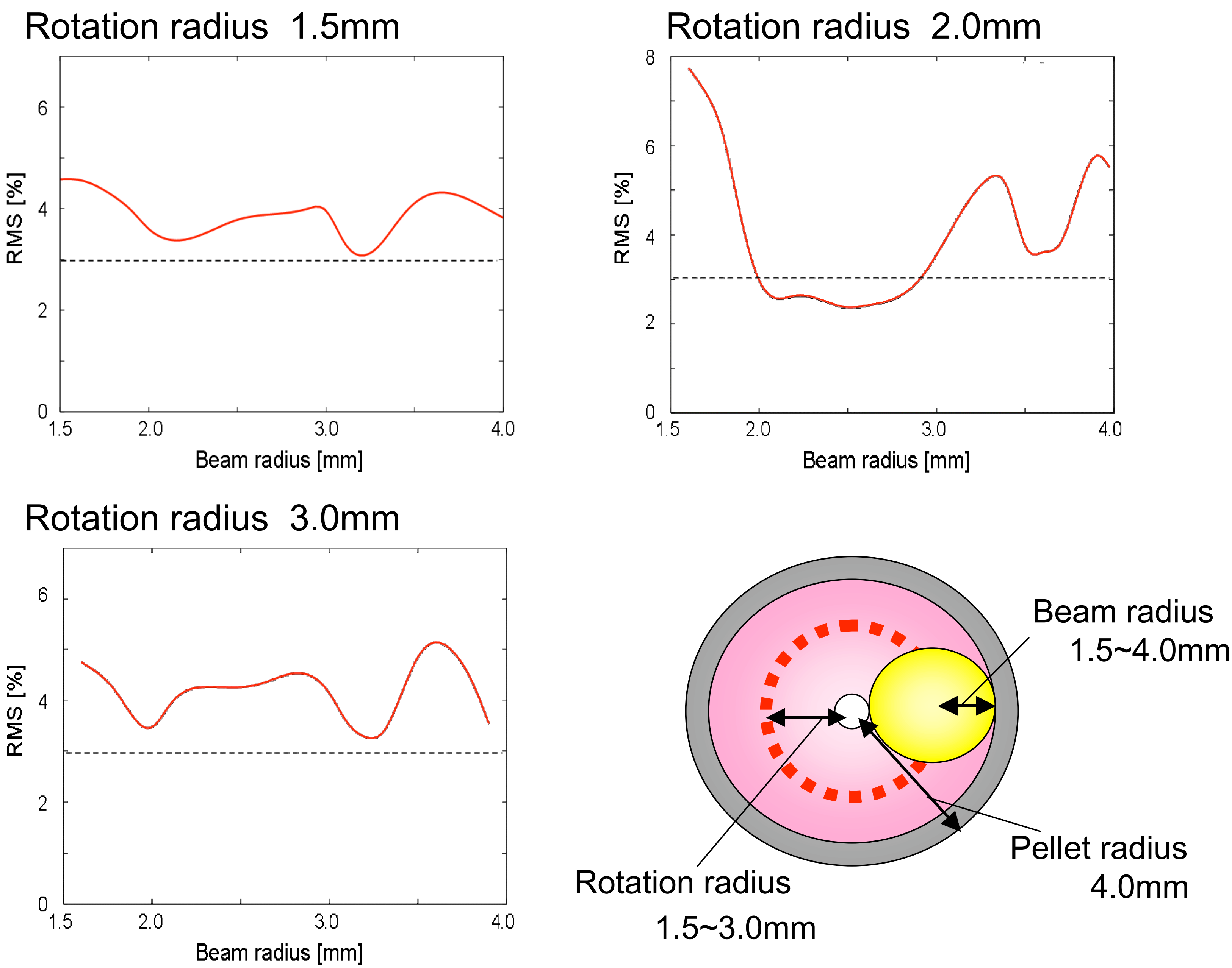
Beam emittance : 1.0 mm-mrad

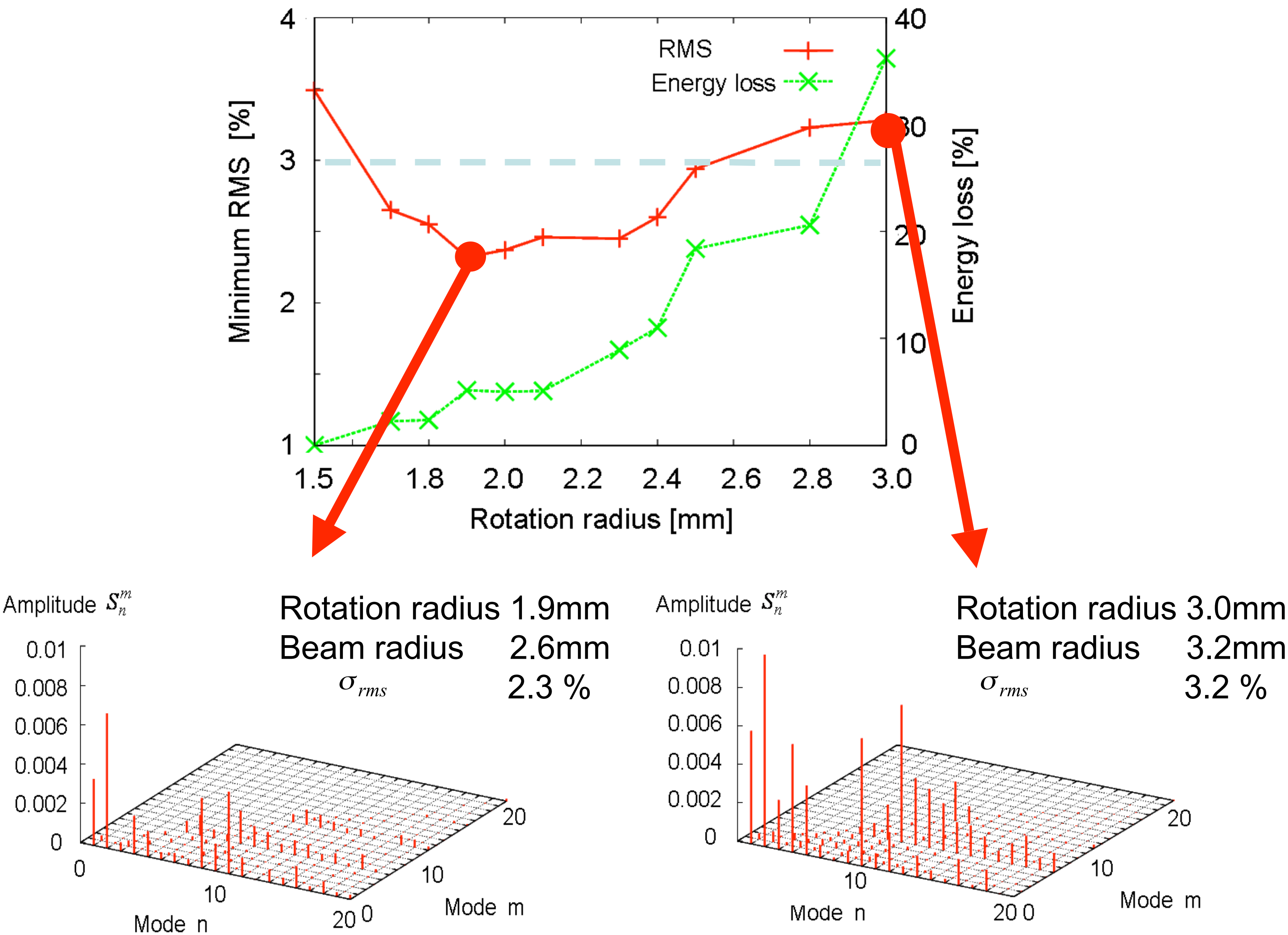
External pellet radius : 4.0mm

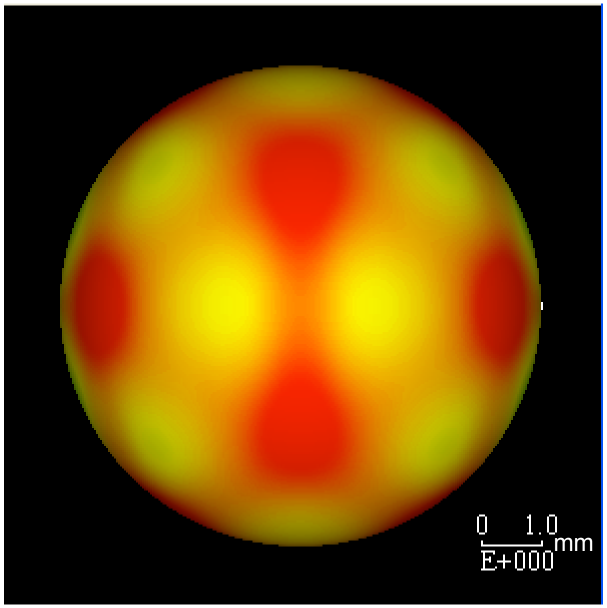
Pellet material : Al



Al pellet structure

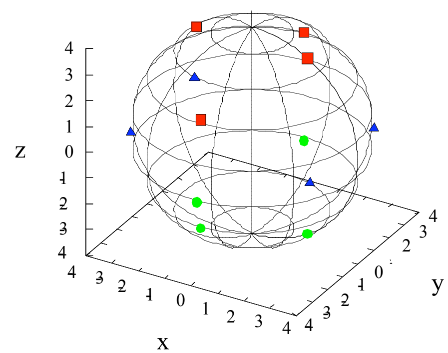

Rotation radius 1.5mm
RMS [%]
0
2
4
6
1.5
2.0
3.0
4.0
Beam radius [mm]
Rotation radius 2.0mm
RMS [%]
0
2
4
6
8
1.5
2.0
3.0
4.0
Beam radius [mm]
Rotation radius 3.0mm
RMS [%]
0
2
4
6
1.5
2.0
3.0
4.0
Beam radius [mm]
Beam radius
1.5~4.0mm
Pellet radius
4.0mm
Rotation radius
1.5~3.0mm


RMS
Energy loss
Minimum RMS [%]
Energy loss [%]
Rotation radius [mm]
4
3
2
1
40
30
20
10
0
1.5
1.8
2.0
2.2
2.4
2.6
2.8
3.0
Amplitude S_n^m
0.01
0.008
0.006
0.004
0.002
0
Mode n
Mode m
Rotation radius 1.9mm
Beam radius 2.6mm
σ_{rms} 2.3 %
Amplitude S_n^m
Rotation radius 3.0mm
Beam radius 3.2mm
σ_{rms} 3.2 %

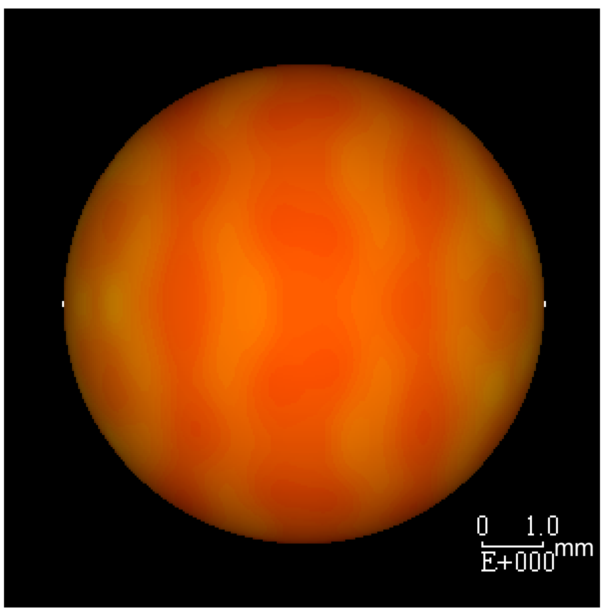


12 beams
Rotation radius 1.9mm
Beam radius 2.6mm
σ_{rms} 8.29%

12-beam

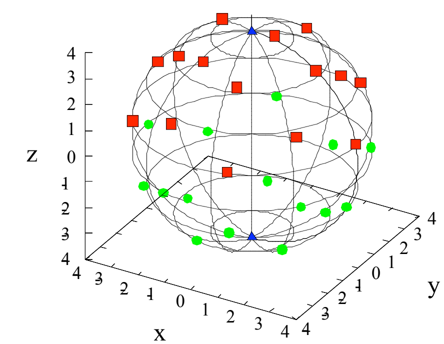


12-HIBs illumination system

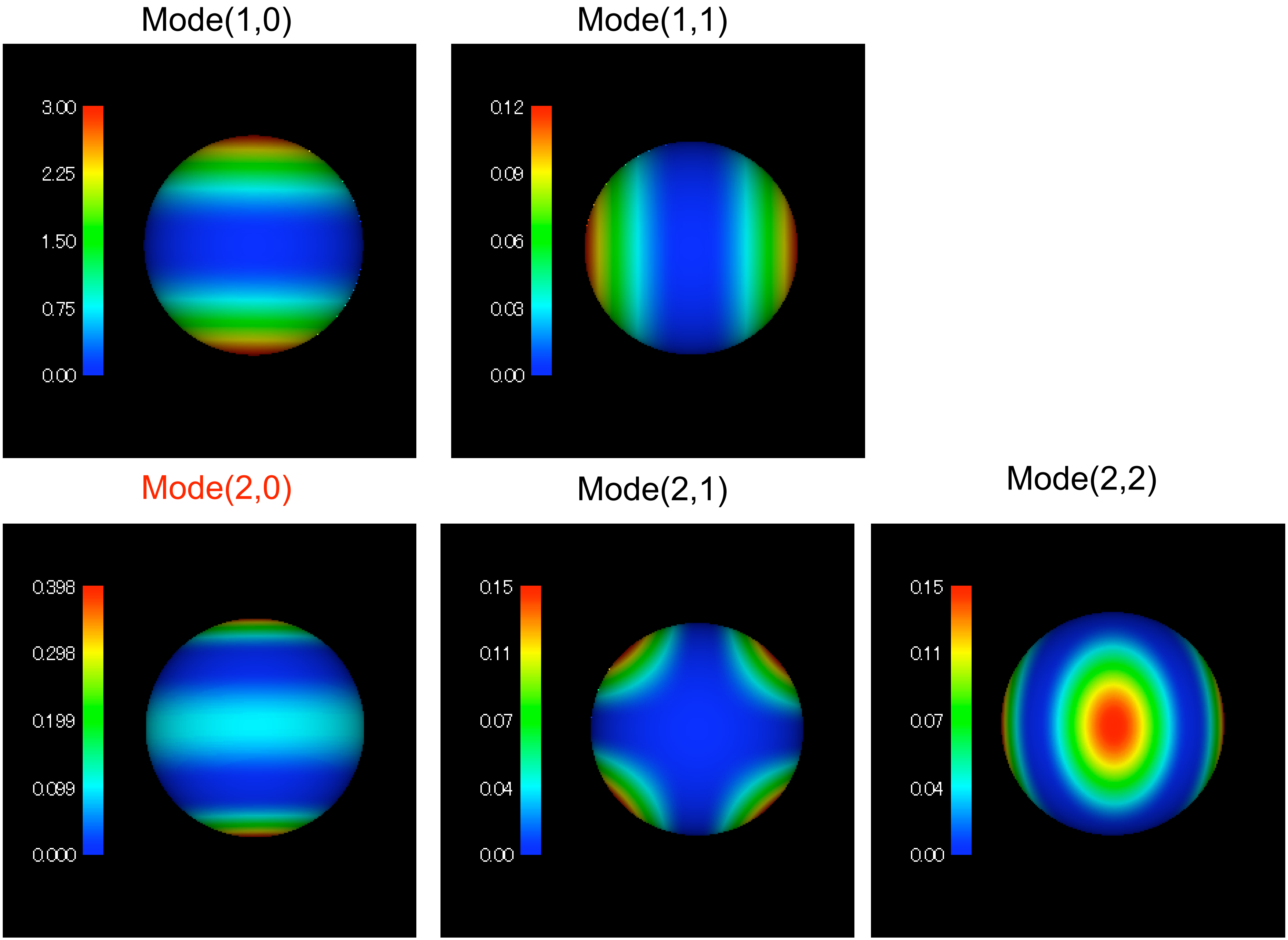


32 beams
Rotation radius 1.9mm
Beam radius 2.6mm
σ_{rms} 2.32%

32-beam

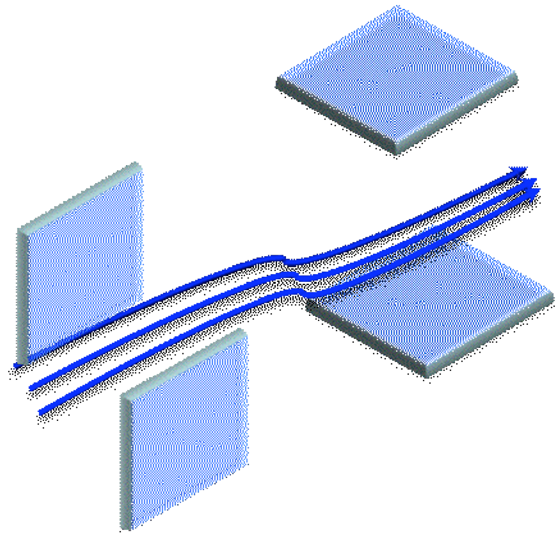


32-HIBs illumination system

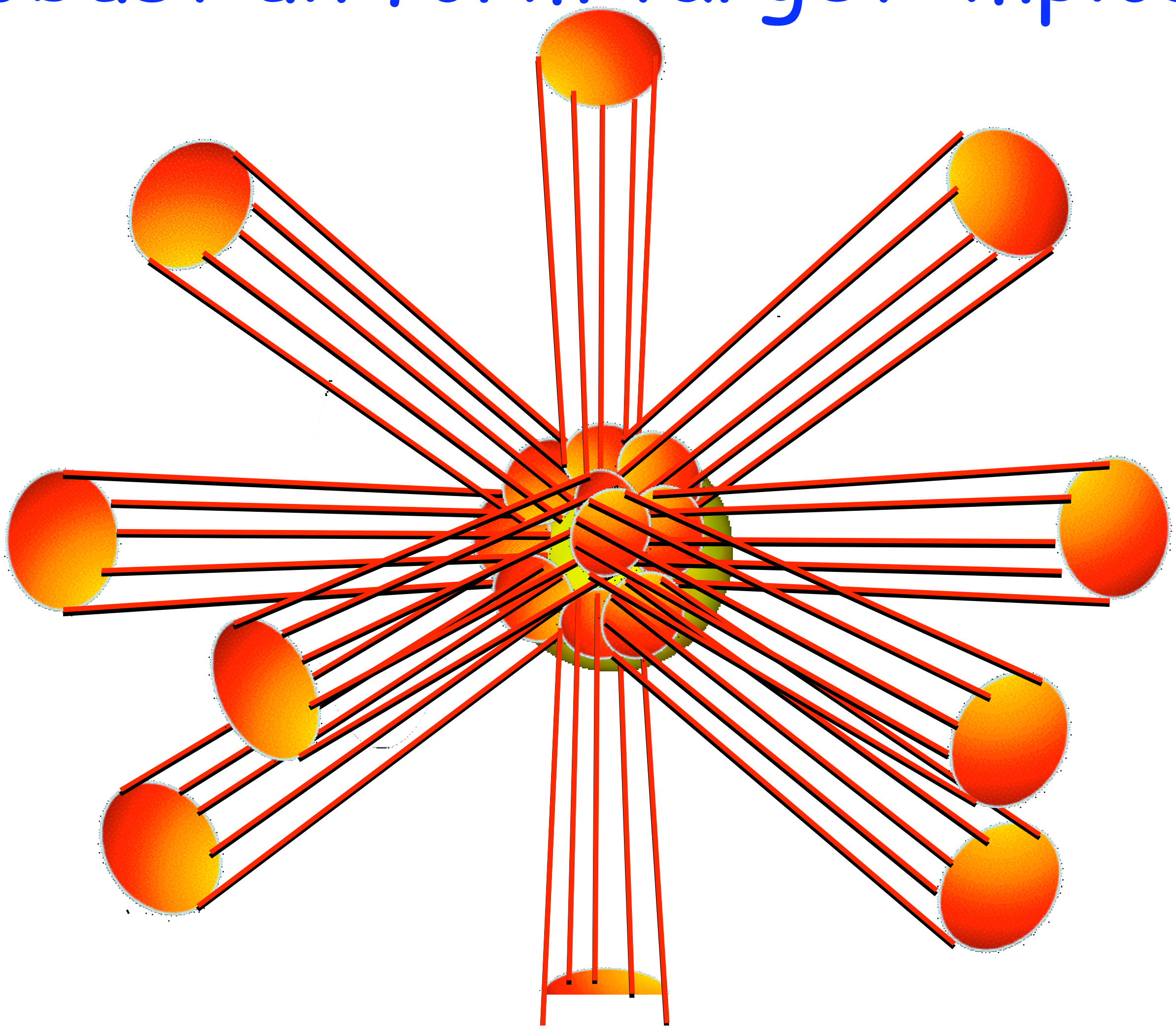

Mode(1,0)
3.00
2.25
1.50
0.75
0.00
Mode(1,1)
0.12
0.09
0.06
0.03
0.00
Mode(2,0)
0.398
0.298
0.199
0.099
0.000
Mode(2,1)
0.15
0.11
0.07
0.04
0.00
Mode(2,2)
0.15
0.11
0.07
0.04
0.00

Summary

- The Rayleigh-Taylor Instability growth can be reduced by the oscillating gravity (acceleration), that may be realized by wobbling HIBs.
- The reduction ratio of the RTI growth depends on the frequency of the gravity oscillation.
- Even in the case of the multi mode gravity perturbation, the RTI growth is reduced by the wobbler.

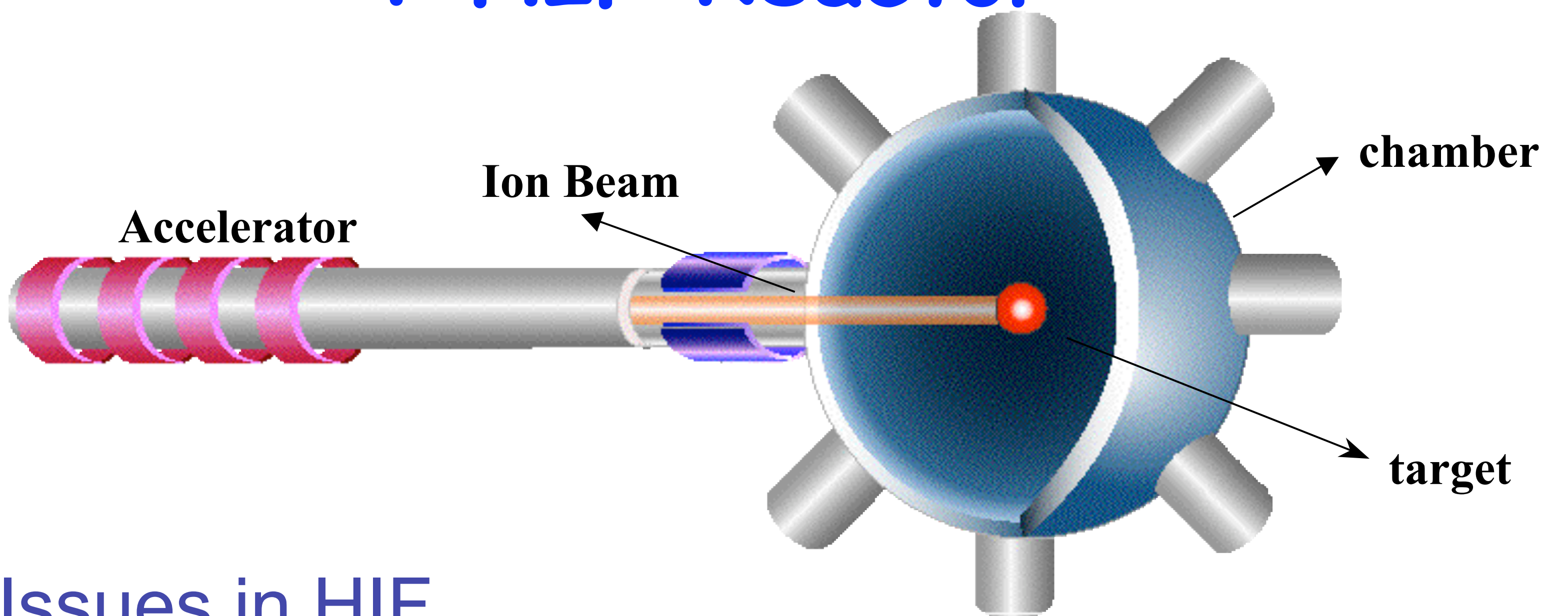


Wobblers may bring
a robust uniform target implosion.



Proposal of
a Conceptual Design of International HIF Reactor?!?
International Collaborative Work!

i-HIF Reactor



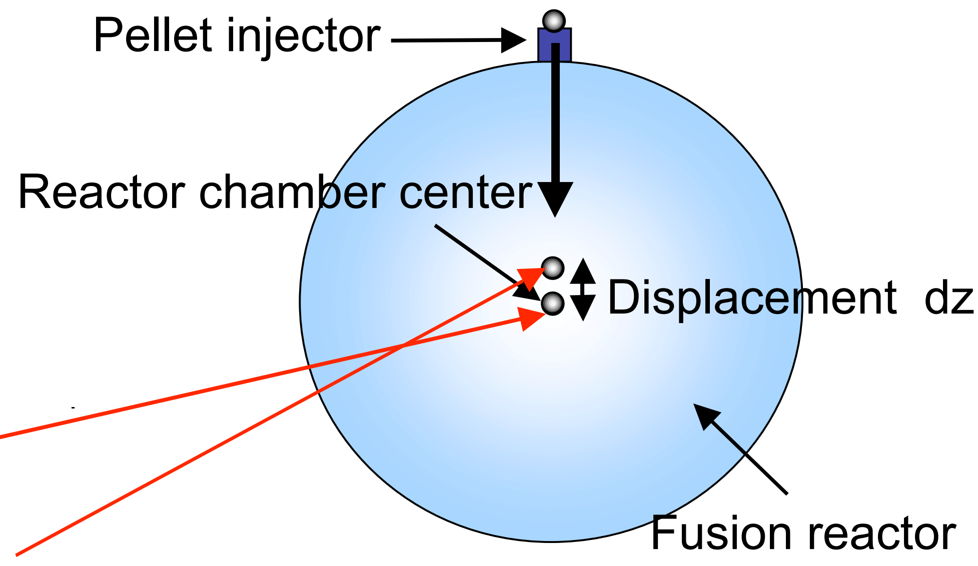
Issues in HIF

/ Particle Accelerator (Scale, Cost, Energy, etc..)
/ Physics of Intense Beam (Focusing & Compression, Emittance growth, etc..)
/ Beam Final Transport (Stable transportation, Interaction with gas, etc..)
/ Target-Plasma Hydrodynamics, stability, beam illumination scheme, robustness, ignition, burning, …
/ Reactor design, wall, T breeding, molten salt, material, neutronics, …
etc..

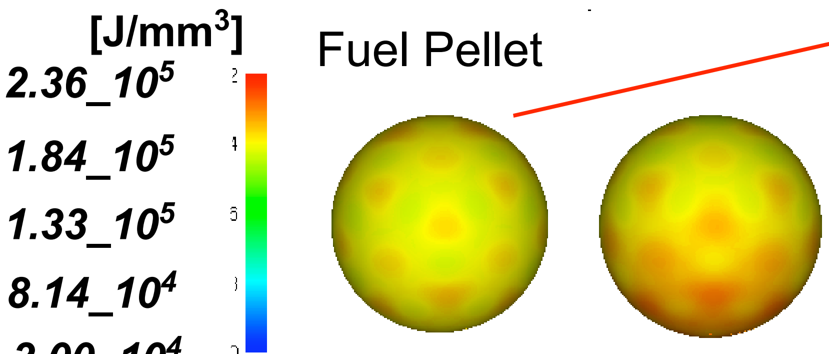
Previous work on uniform HIB illumination

_HIB illumination non-uniformity

< a few %



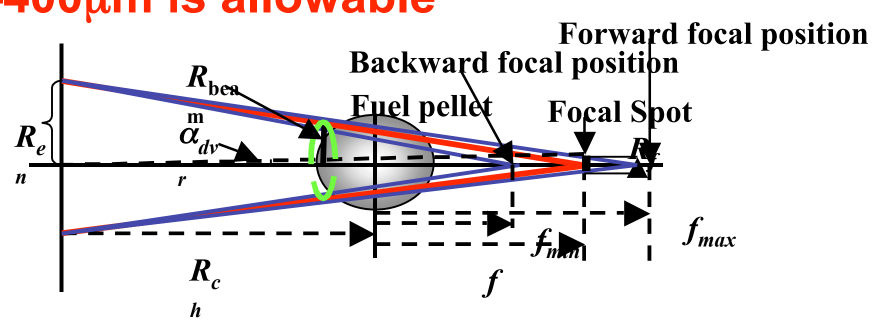
_IFE reactor



(a)_dz = 0[μm] **(b)_dz = 100[μm]**

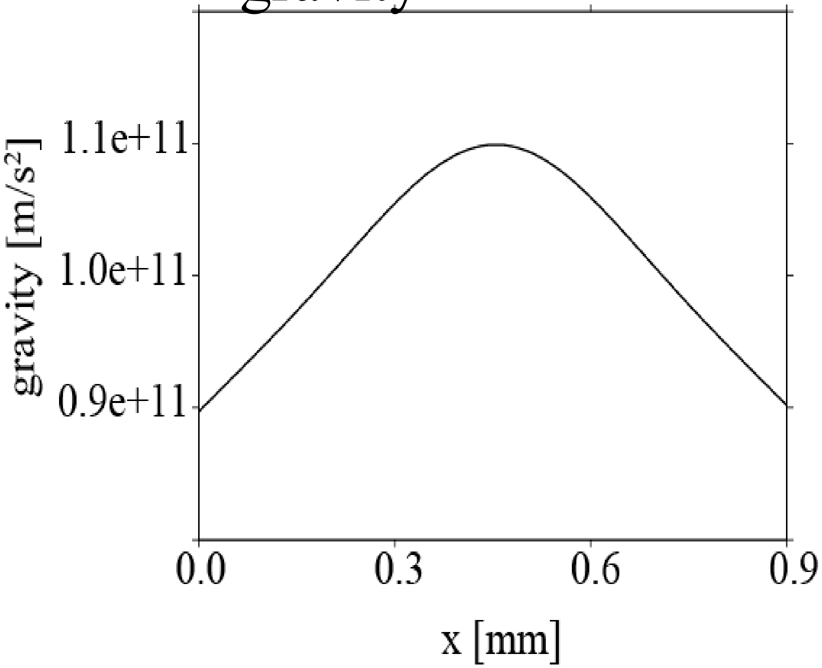
Conventional illumination pattern => ~ **50-100μm** => non-uniformity > **3.0%**

Our results => ~ **300-400μm is allowable**

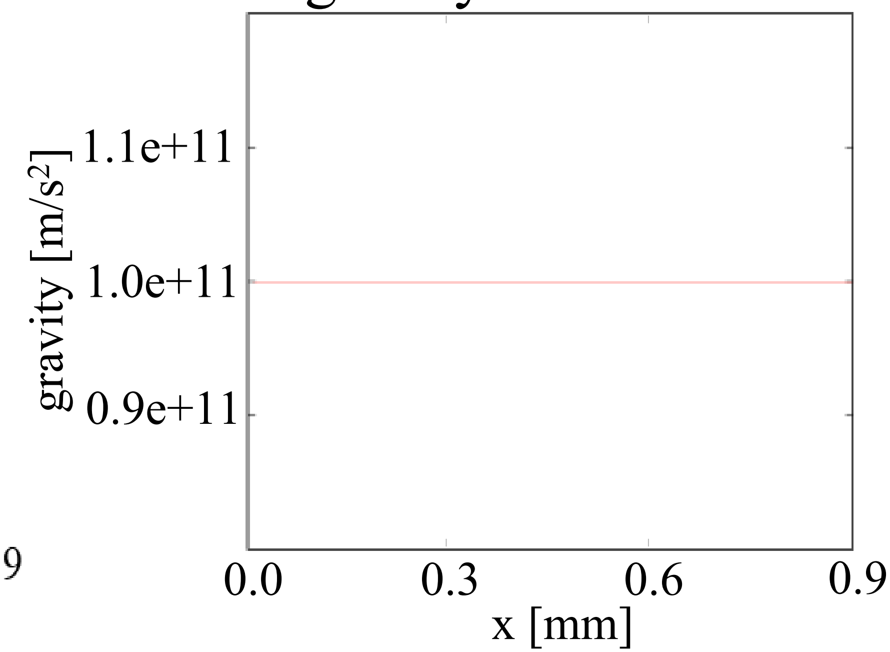


Sample (beam profile) Simulation [constant]

gravity



gravity



parameter

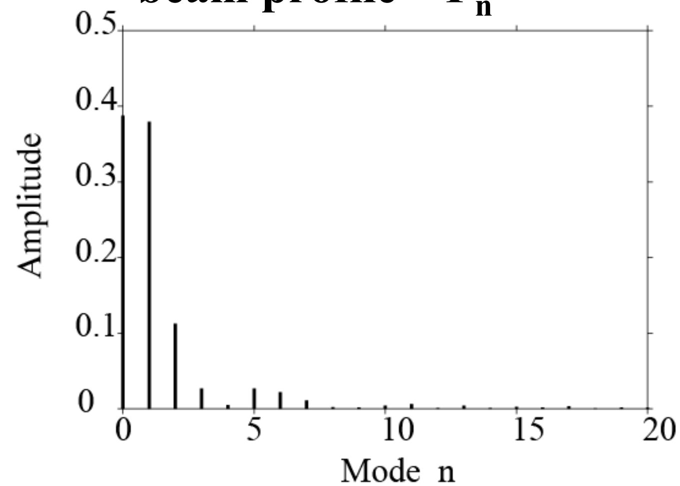
ρ_{High} : 1000 $[kg/m^3]$

ρ_{Low} : 300 $[kg/m^3]$

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

f : 10^7 $[Hz]$

beam profile P_n



Sample (beam profile) Comparison (t=0.2 [μ sec])

density

vorticity

constant

oscillation

(γ [Hz])