Wobbling HIB Illumination Uniformity

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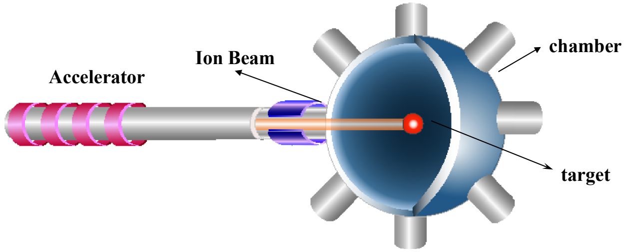
Acknowledgements: Friends in HIF-VNL in U.S.A.

Purpose



Improve HIB illumination non-uniformity of wobblers' initial imprint, which induces implosion non-uniformity

Background

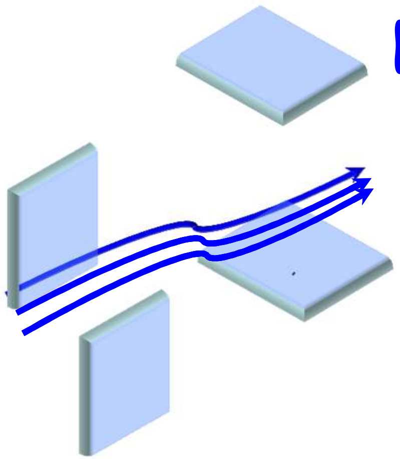
Precisely controllable HIB: pulse shape, particle energy, beam axis, etc.

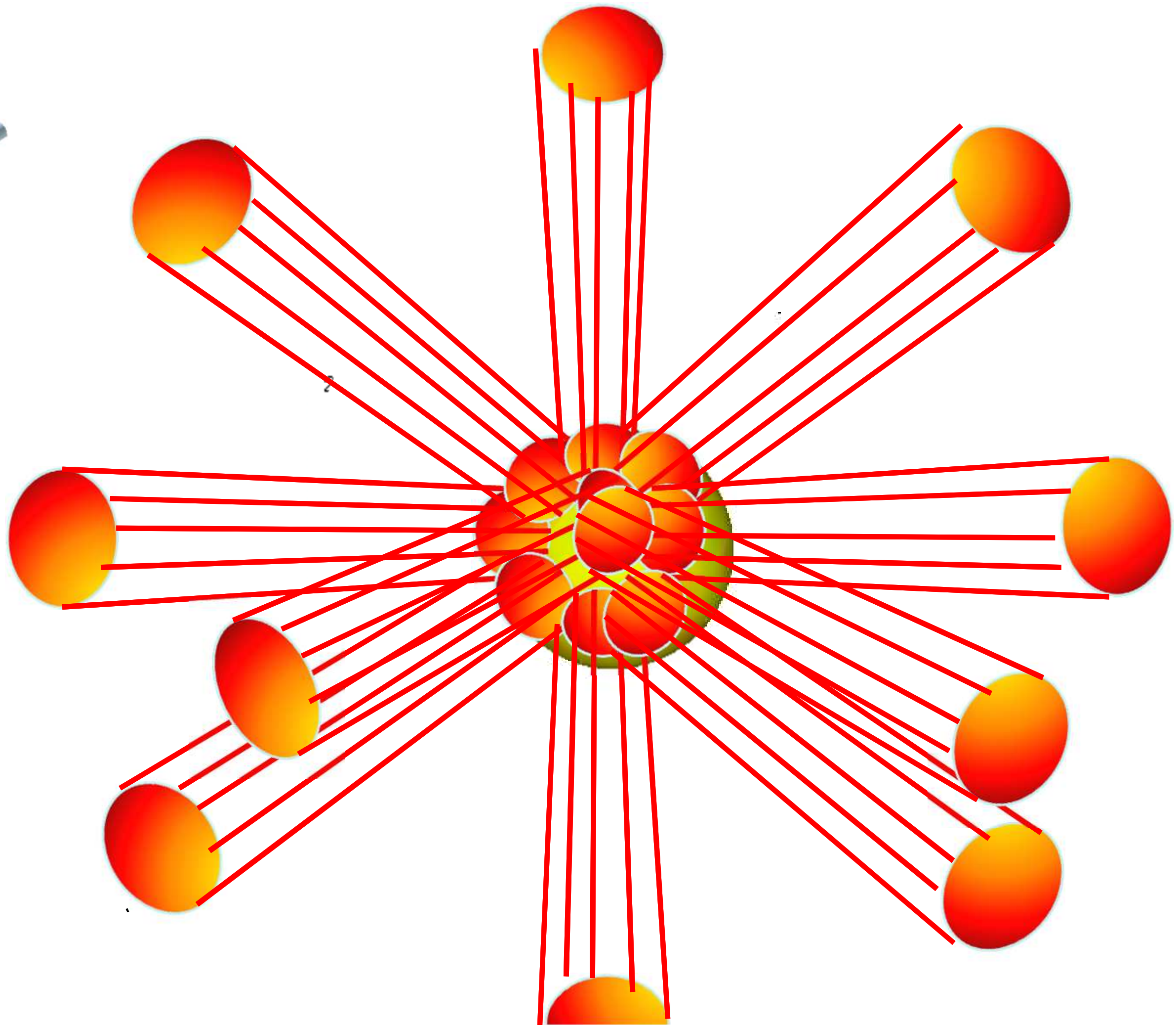
Recently Wobbling HIBs were proposed to smooth HIB illumination nonuniformity & R-T growth reduction. <- /S.Kawata, et al, /J. Lunge, et al, /H. Qing, etc.

J. Lunge & G. Logan found a very-good uniformity of HIBs illumination for time-averaged HIBs on a target.

-> A large HIBs-illumination nonuniformity by the Initial imprint ~ 15% or
-> Initial imprint should be reduced.

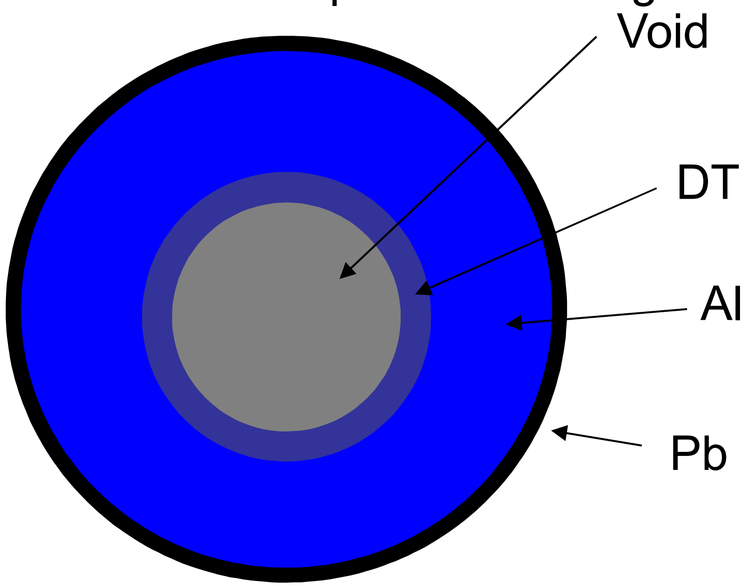
Wobbling Heavy Ion Beams may reduce the R-T growth.

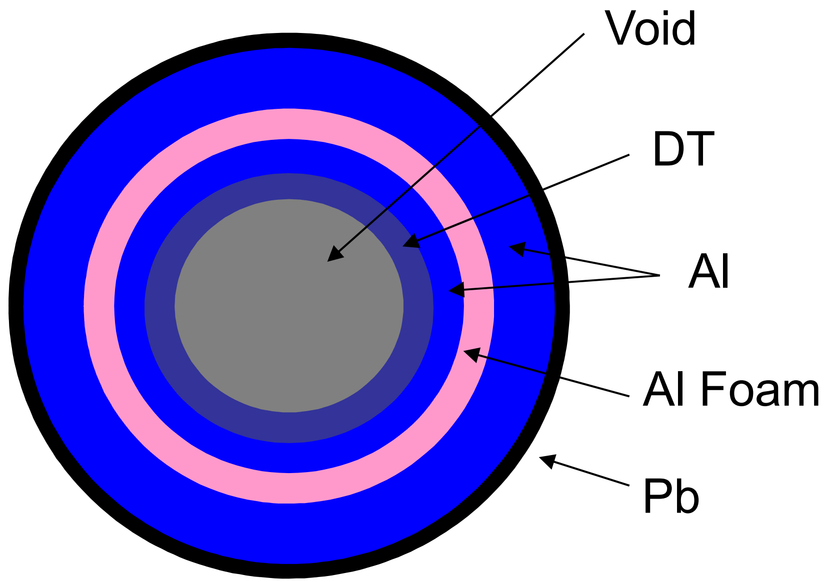




Background

Examples of HIF target design

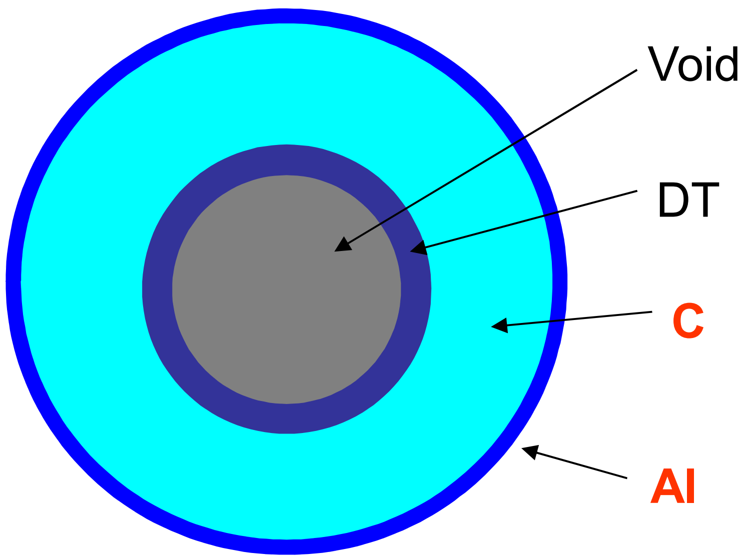




Direct-indirect hybrid implosion

HIB input energy is 4MJ,

-> Gain ~45.



HIB input energy is 1.8MJ,

-> Gain ~223.

PHYSICS OF PLASMAS 15, 072701 (2008)

Direct drive heavy-ion-beam inertial fusion at high coupling efficiency

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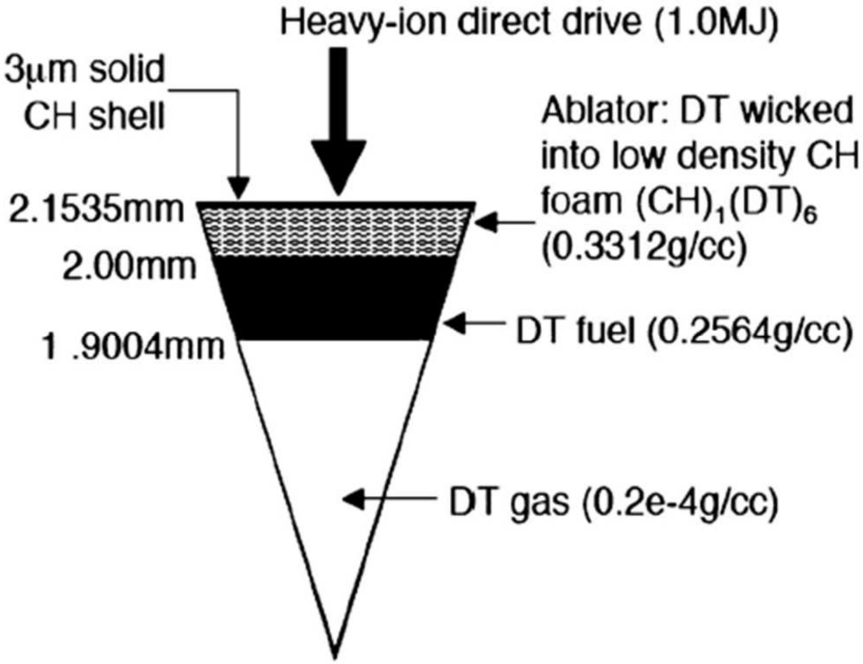
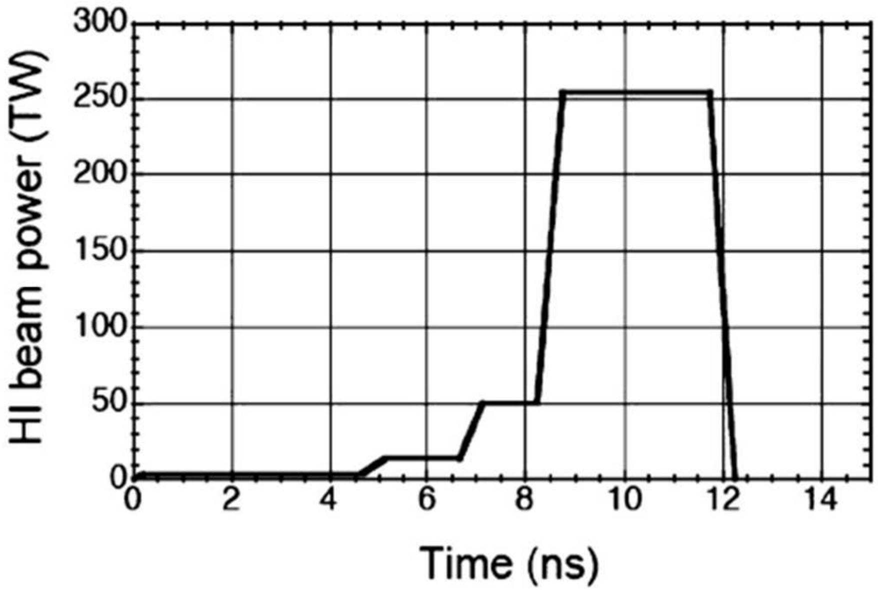
[2]*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*



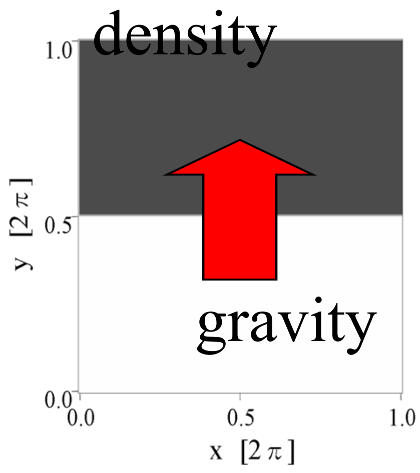


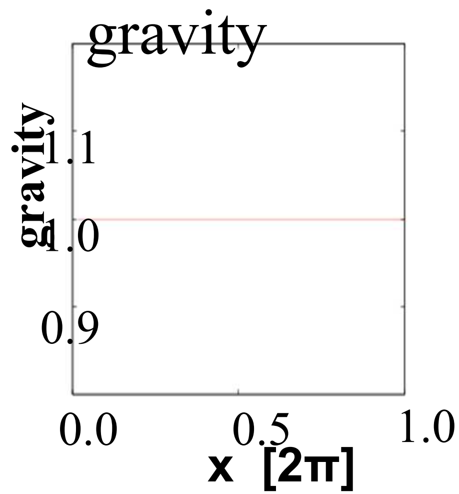
high coupling efficiencies shell kinetic energy/
incident beam energy of 16% to 18%!!!

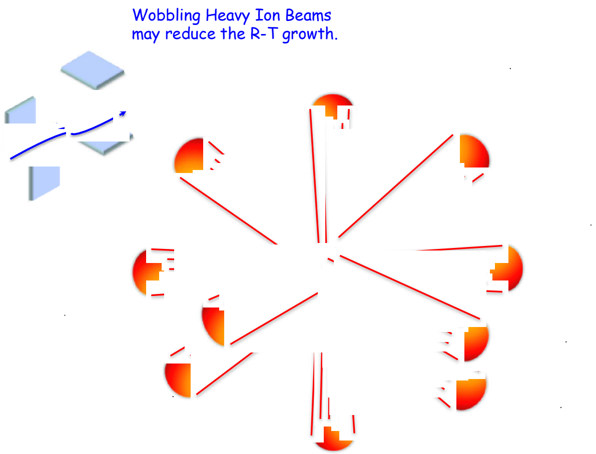
Background

R-T instability growth control by Wobblers

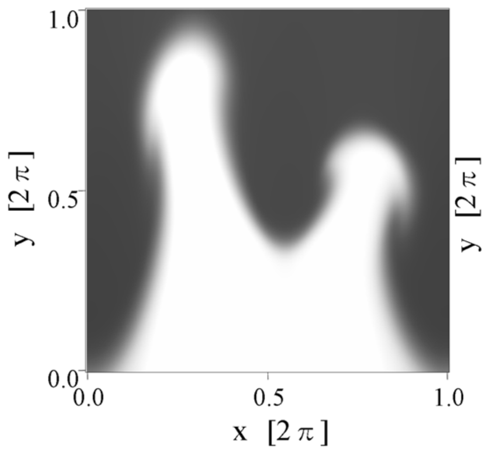
$g = g_0 + \delta g$



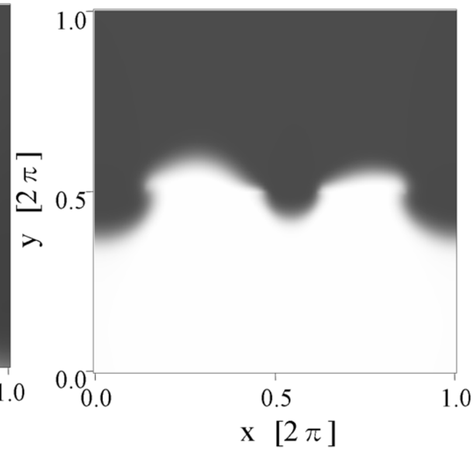




Normal R-T growth

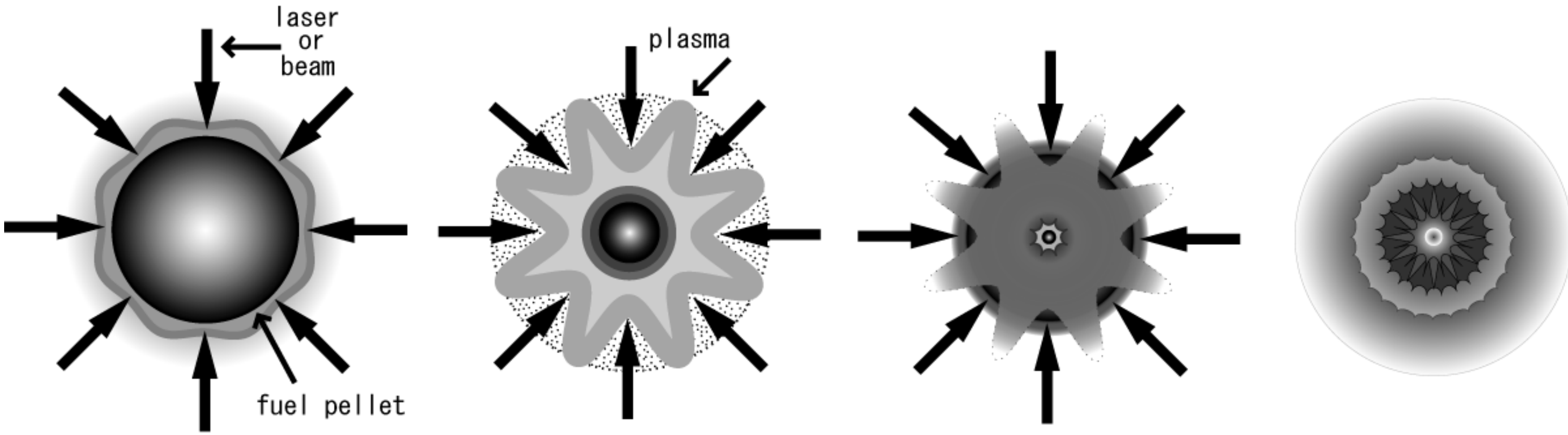


R-T growth under δg oscillation



Wobbling HIBs ->

1. smoothing of illumination nonuniformity
2. R-T growth control



①Illumination ②Implosion ③Ignition ④Burning

Background

PRL **104**, 254801 (2010) PHYSICAL REVIEW LETTERS week ending 25 JUNE 2010

Centroid and Envelope Dynamics of High-Intensity Charged-Particle Beams in an External Focusing Lattice and Oscillating Wobbler

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(Received 14 January 2010; published 22 June 2010)

The centroid and envelope dynamics of a high-intensity charged-particle beam are investigated as a beam smoothing technique to achieve uniform illumination over a suitably chosen region of the target for applications to ion-beam-driven high energy density physics and heavy ion fusion. The motion of the beam centroid projected onto the target follows a smooth pattern to achieve the desired illumination, for improved stability properties during the beam-target interaction. The centroid dynamics is controlled by an oscillating "wobbler," a set of electrically biased plates driven by rf voltage.

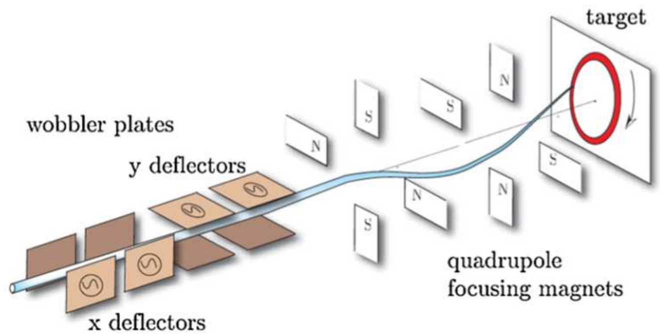
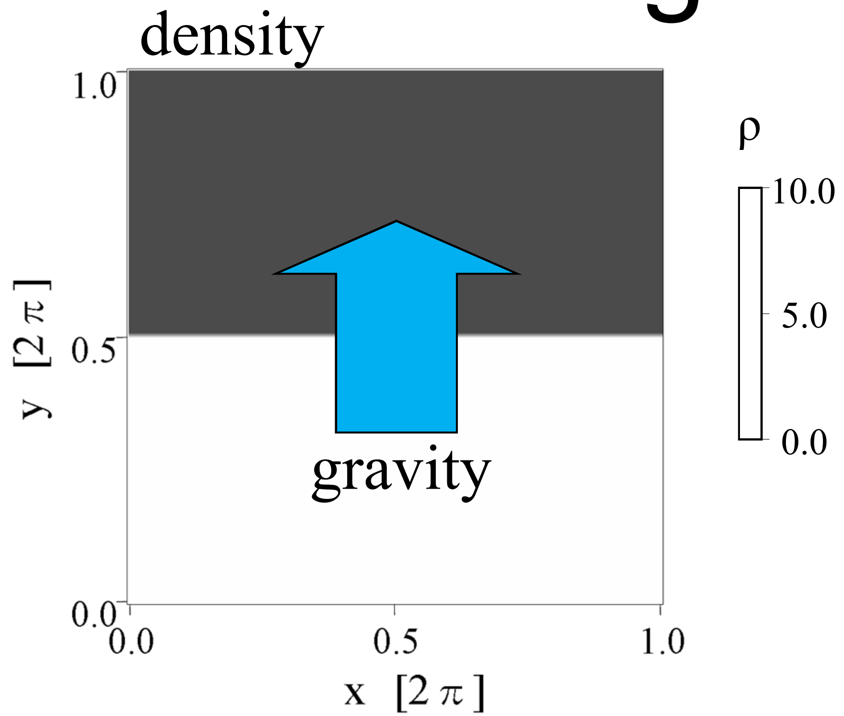
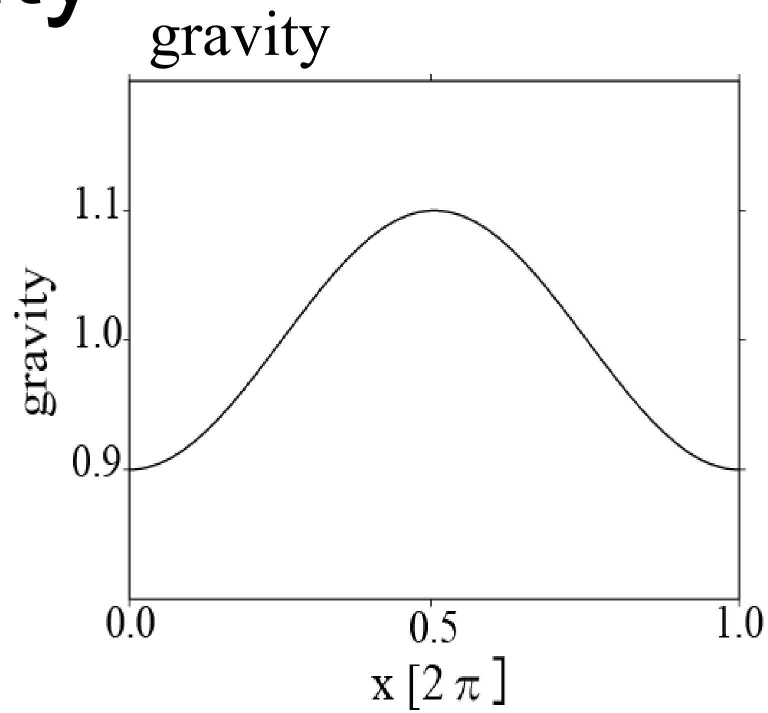


FIG. 1 (color). Quadrupole focusing lattice and wobbler system. The motion of the centroid projected onto the target follows a smooth pattern in order to achieve uniform illumination over a suitably chosen region of the target.

Simulation model - constant gravity -





The calculation parameters are

$\rho_{High} : 10$

$\rho_{Low} : 3$

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

$g_0 : 1$

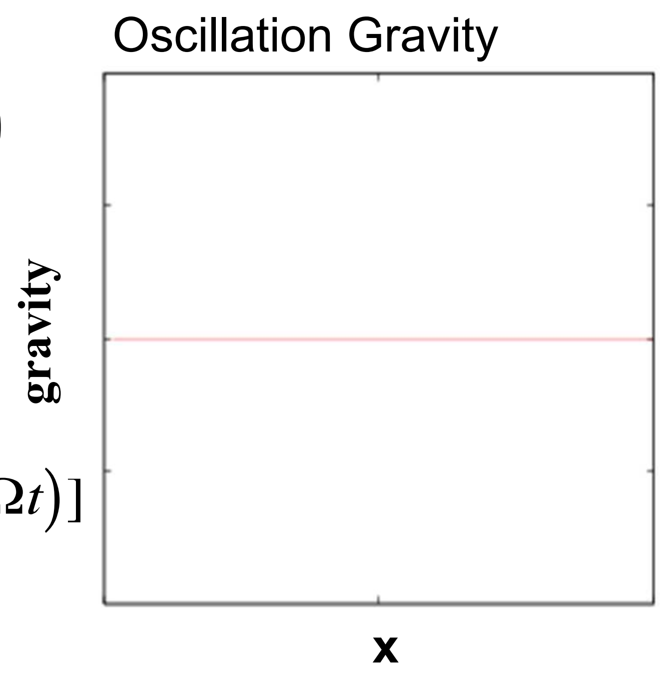
$k : 1$

Control of RTI - Oscillating gravity -

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

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

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



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

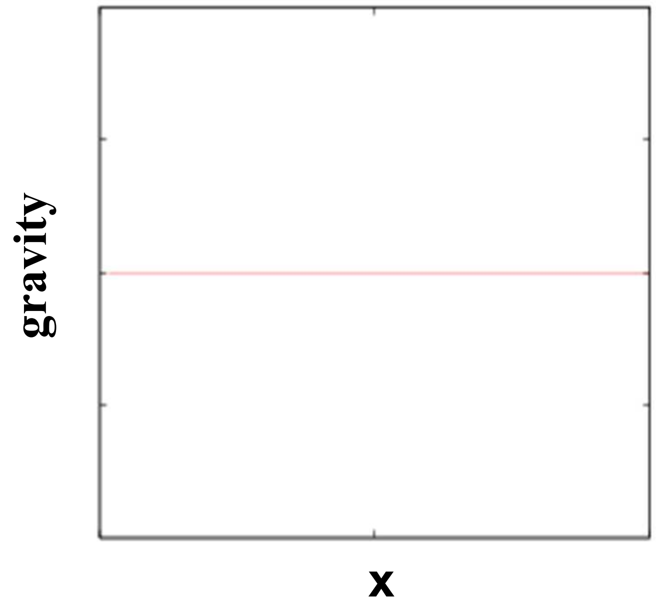
w_0 : *initial velocity* $\quad \delta g$: *non-uniform gravity* $\quad t$: *time*

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

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



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

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

$$Growth\ Reduction\ Ratio \approx \frac{\gamma}{\Omega} \quad for \quad \gamma << \Omega$$

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

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

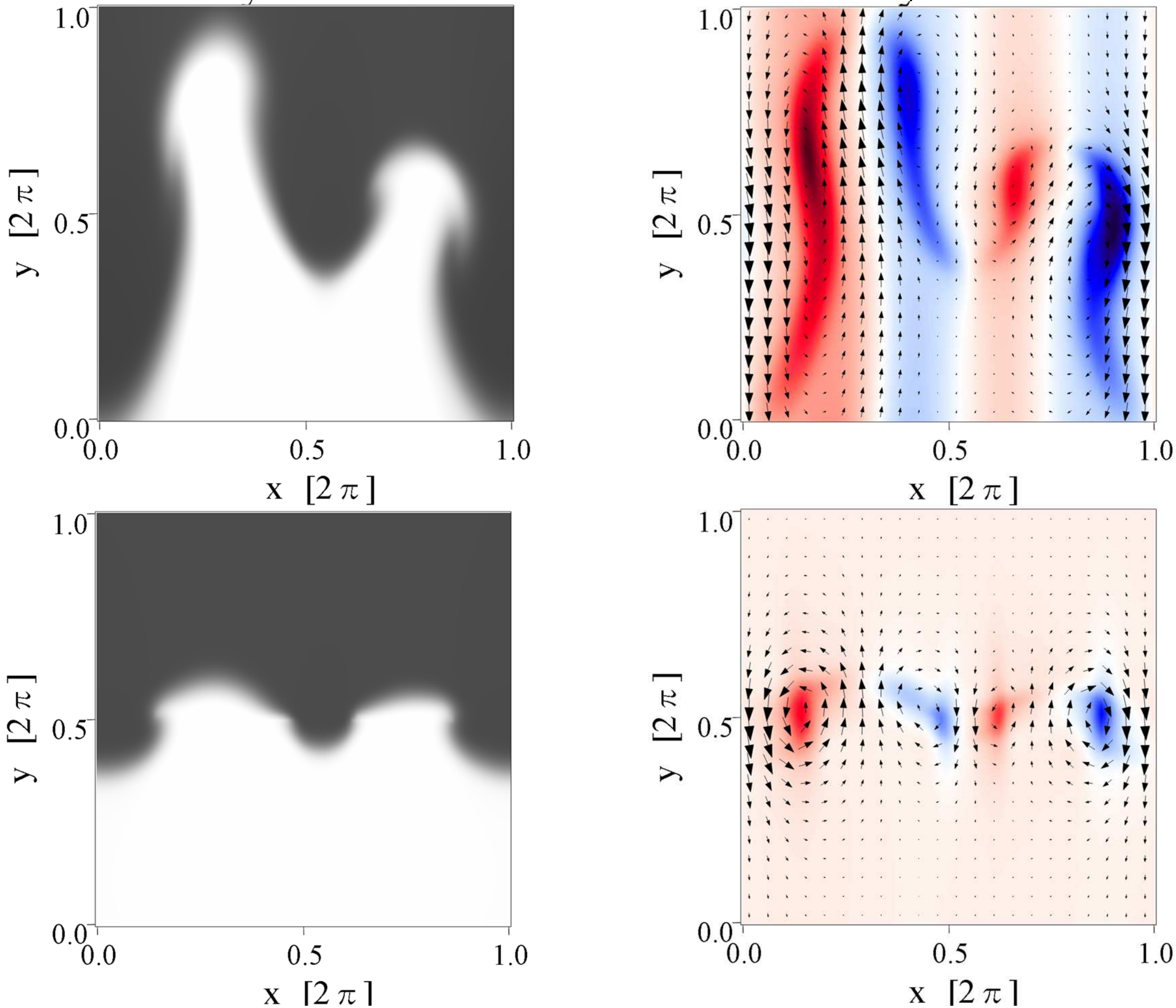
From the equation, when the gravity oscillation frequency *f* is increased, the RTI perturbation velocity *w* decreases.

Multi Mode Comparison (t=5 [1/γ])

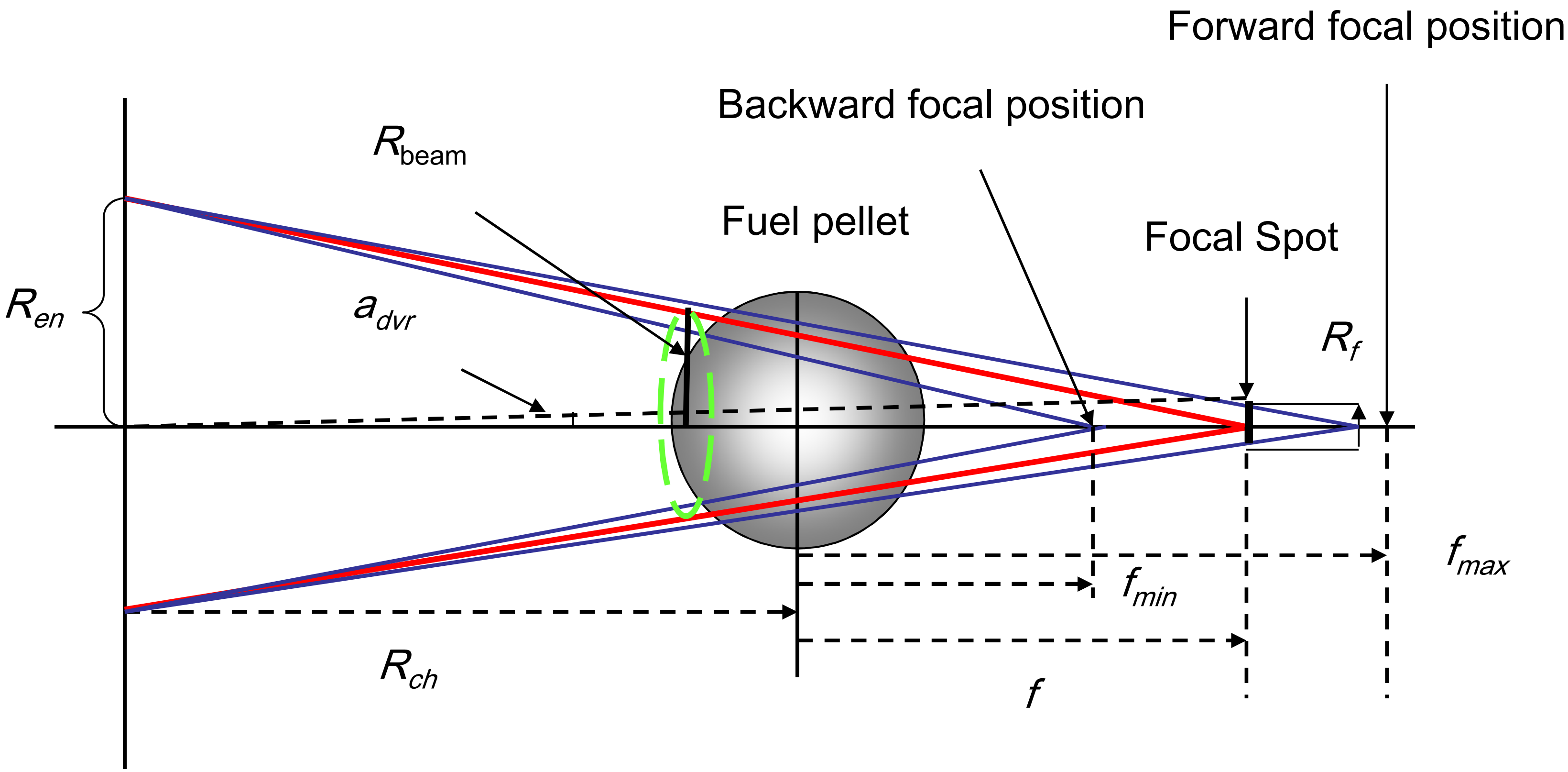
density | vorticity

constant

oscillation
(γ[Hz])

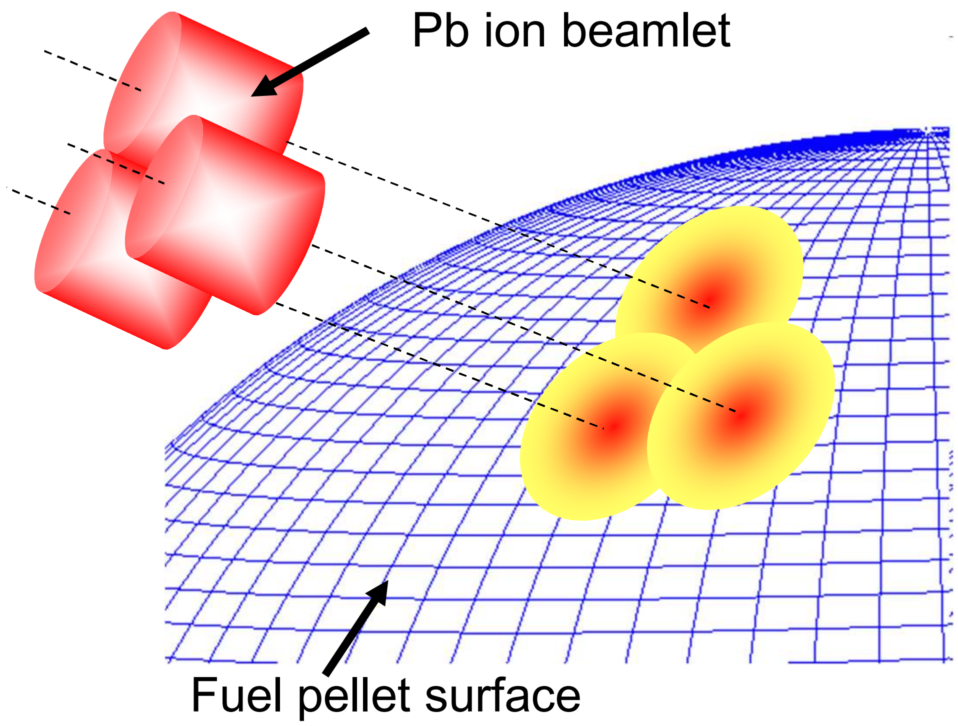


HIB-Fuel pellet interaction

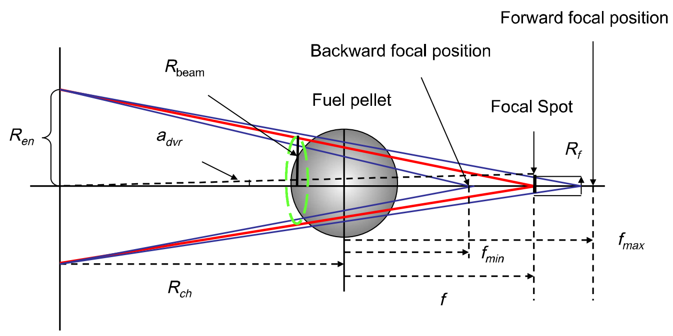


HIB illumination model

2．HIB-Fuel pellet interaction (2)



HIB-Fuel pellet interaction



HIB illumination model

Calculation procedure

1. A beam is divided into many beamlets
2. Calculation of beam particle trajectories
3. Calculation of stopping power
4. Energy deposition on to the fuel pellet

PHYSICS OF PLASMAS **16**, 033109 (2009)

Nonuniformity for rotated beam illumination in directly driven heavy-ion fusion

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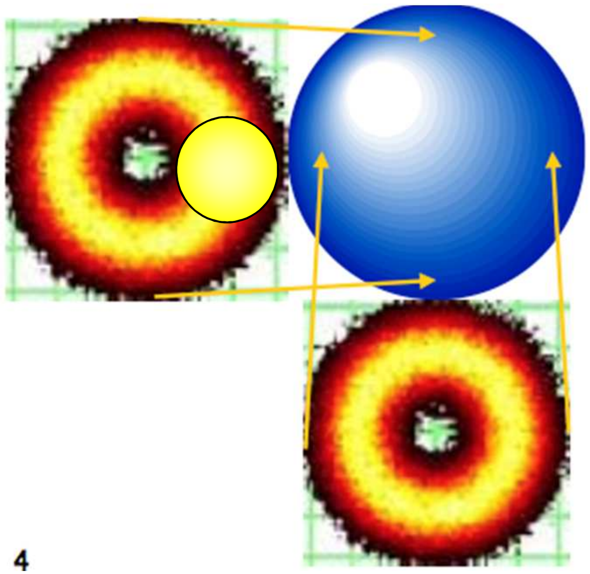
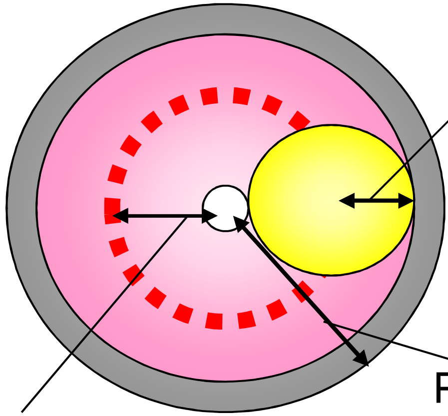
Lawrence Berkeley National Laboratory and Virtual National Laboratory for Heavy Ion Fusion, Berkeley, California 94720, USA

60 HIBs -> <1% HIB illumination non-uniformity





Parameters

Pb^+ ion beam

Beam number : 32

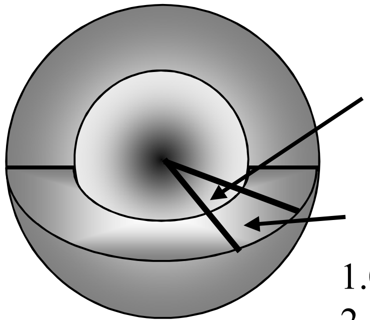
Beam particle energy : 8GeV

Beam particle density distribution : Gaussian

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

External pellet radius : 4.0mm

Pellet material : Al



Al pellet structure

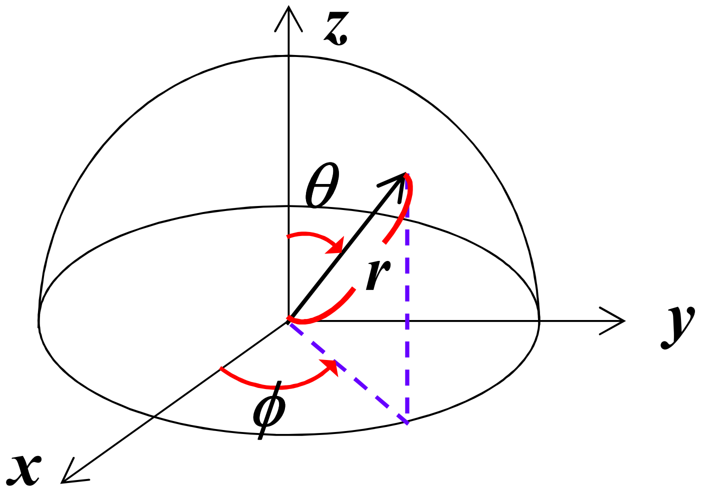
32 HIBs

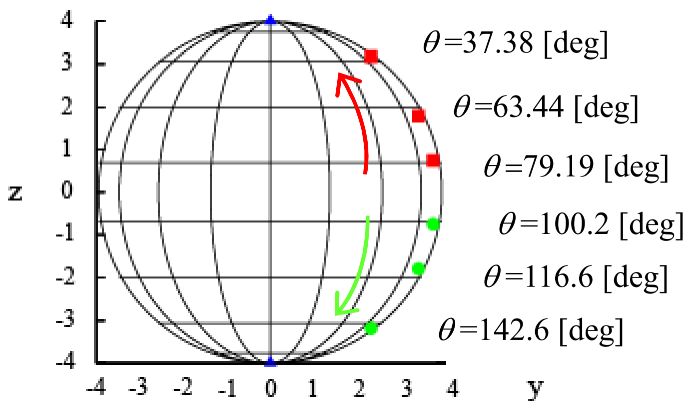
ref.: Skupsky & Lee, JAP 54(1983)3662.

Optimization for Suppression of HIB illumination non-uniformity

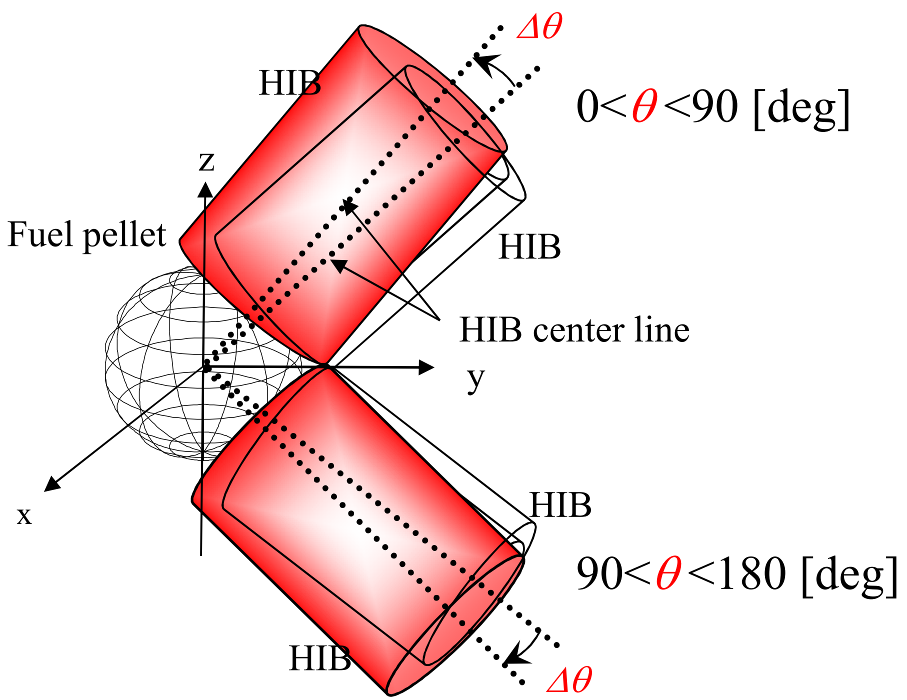
HIB radius larger than external pellet radius (4.0mm)

Find optimal θ





HIB illumination angle in θ direction at the 32-beams

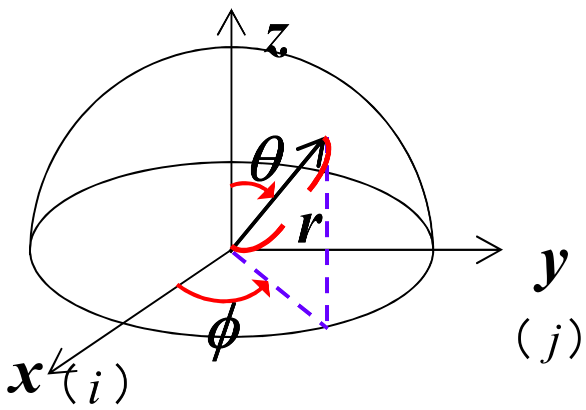


Schematic diagram of HIB illumination arrangement in the θ direction

Evaluation method non-uniformity

We define the total relative root-mean-square as follows

$$\sigma_i = \frac{1}{\langle F_i \rangle} \sqrt{\frac{1}{N_j} \sum_{j=1}^{N_j} \left(F_{ij} - \langle F_i \rangle \right)^2}$$



F_{ij} : Physical quantity (radiation temperature, ion temperature, density, pressure)

$\langle F_i \rangle$: Mean physical quantity on i surface

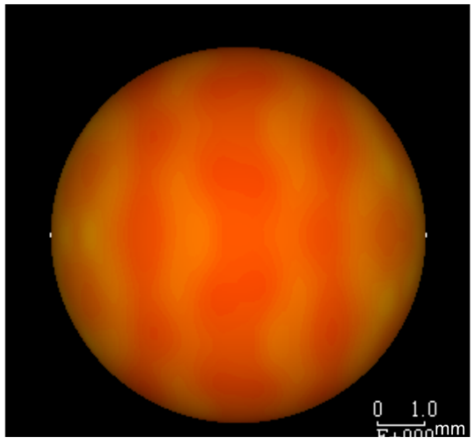
N : total mesh number

The non-uniformity in the Al

$$\sigma = \sum_{i=1}^{N_i} w_i \sigma_i$$

The weight function :

$$w_i = \frac{\sum_{j=1}^{N_j} F_{i,j}}{\sum_{i=1}^{N_i} \sum_{j=1}^{N_j} F_{i,j}}$$

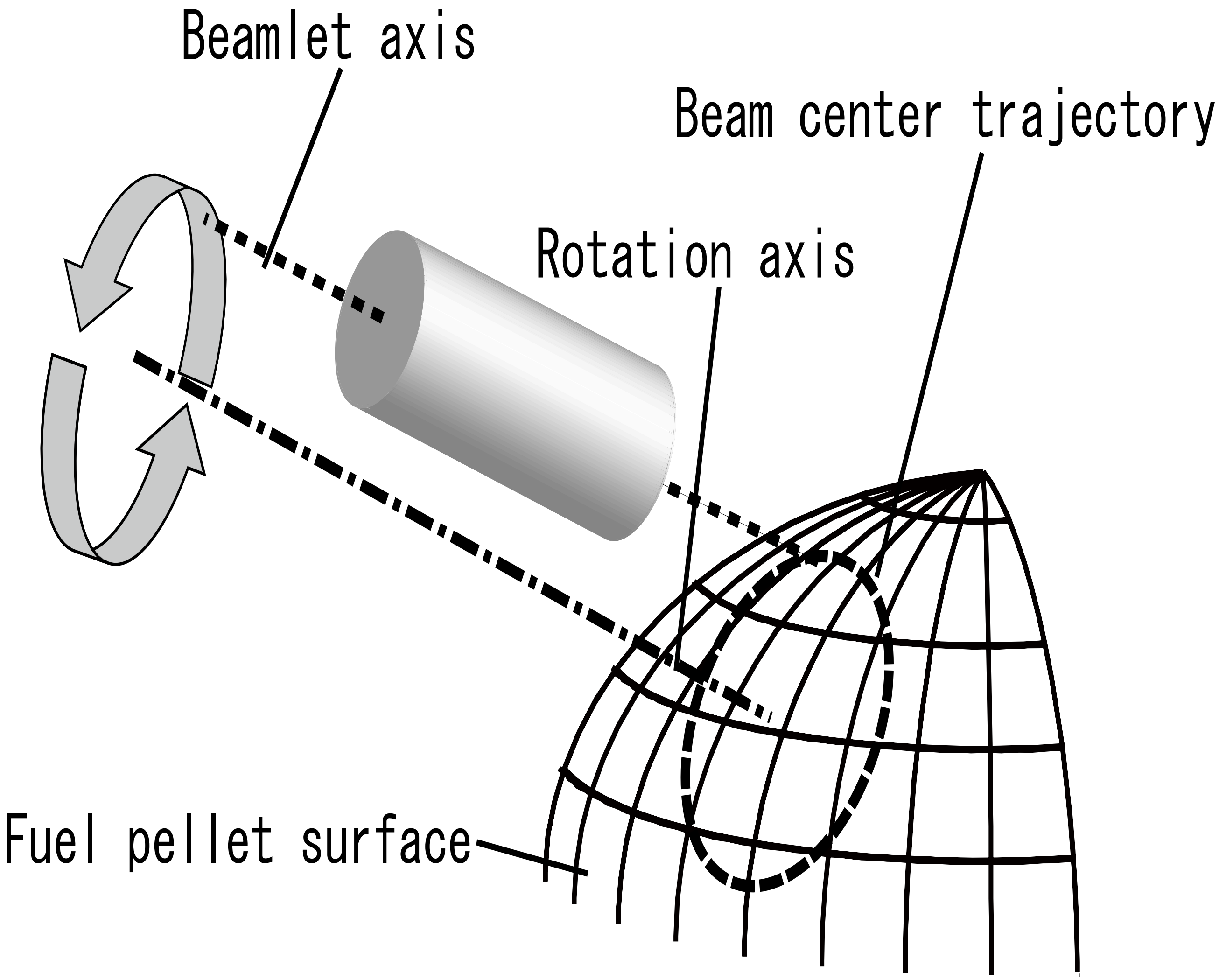


32 beams
Rotation radius 1.9mm
Beam radius 2.6mm
σ_{rms} 2.32%

32-beam

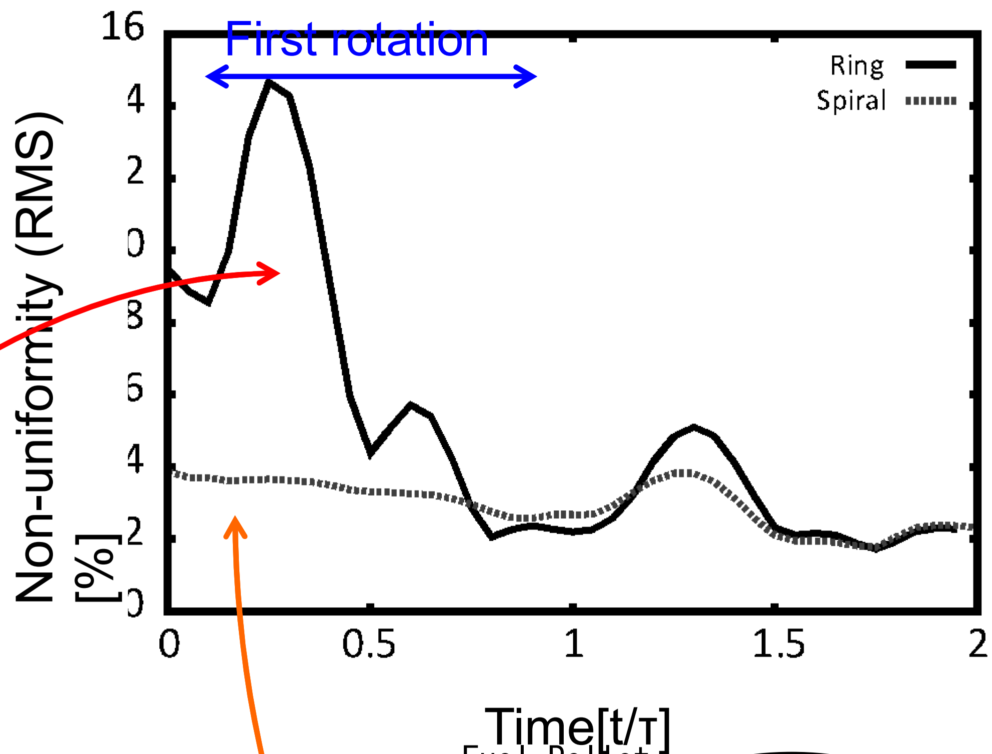
32-HIBs illumination system

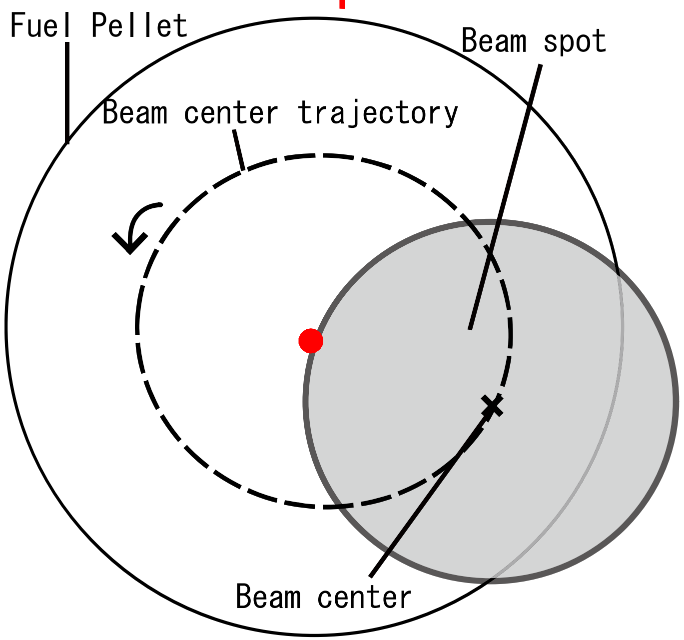
Image of Wobbling Heayv Ion Beam

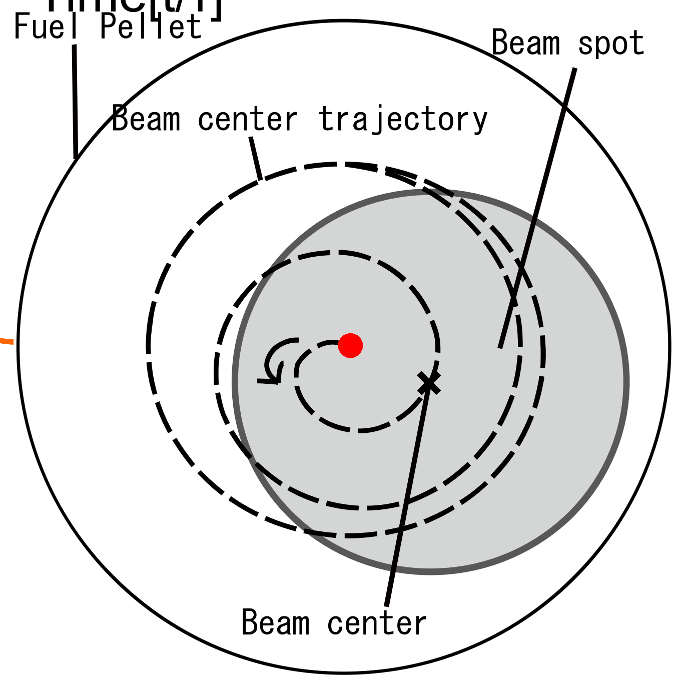


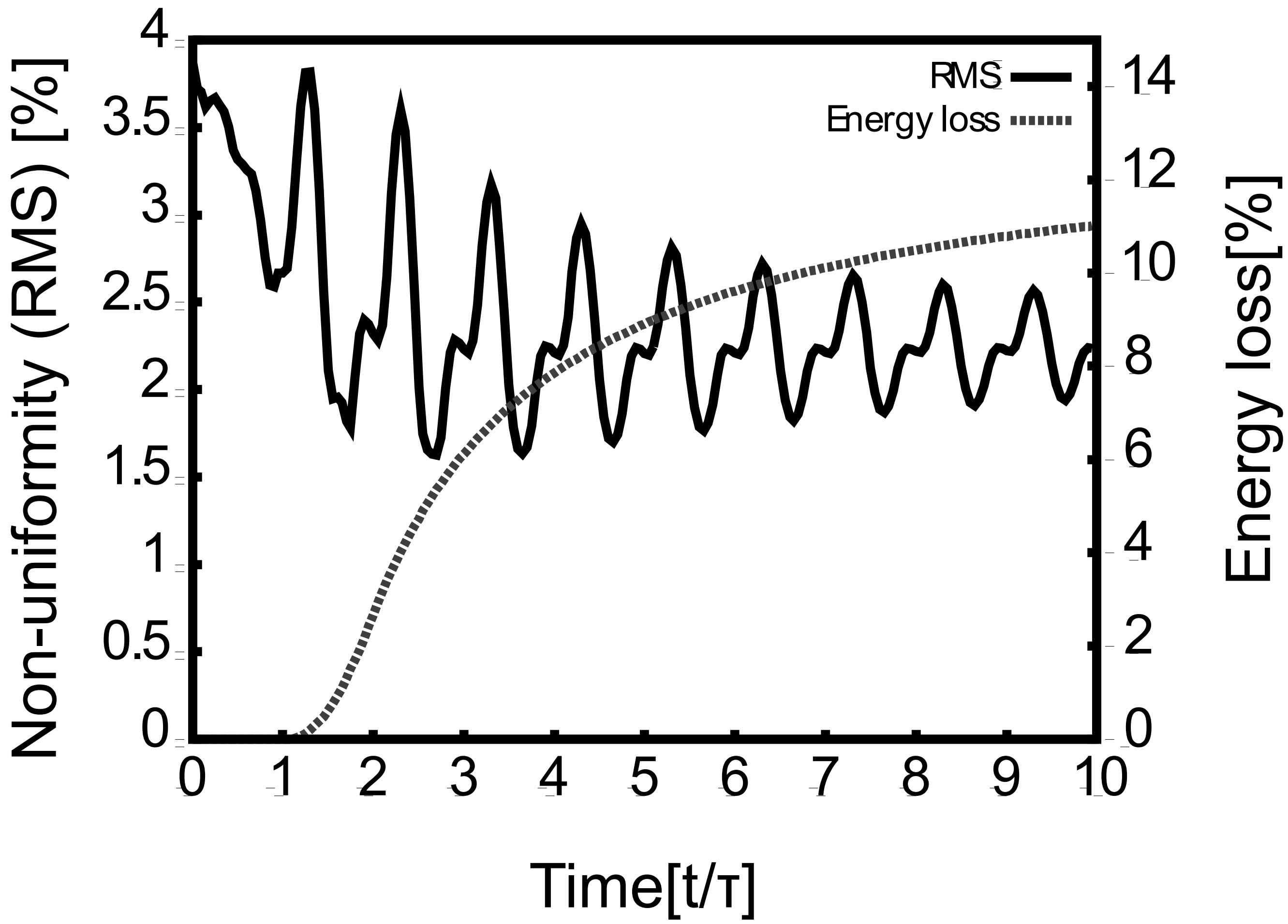
Initial imprint was huge.

<- Spiral HIBs reduce Imprint.

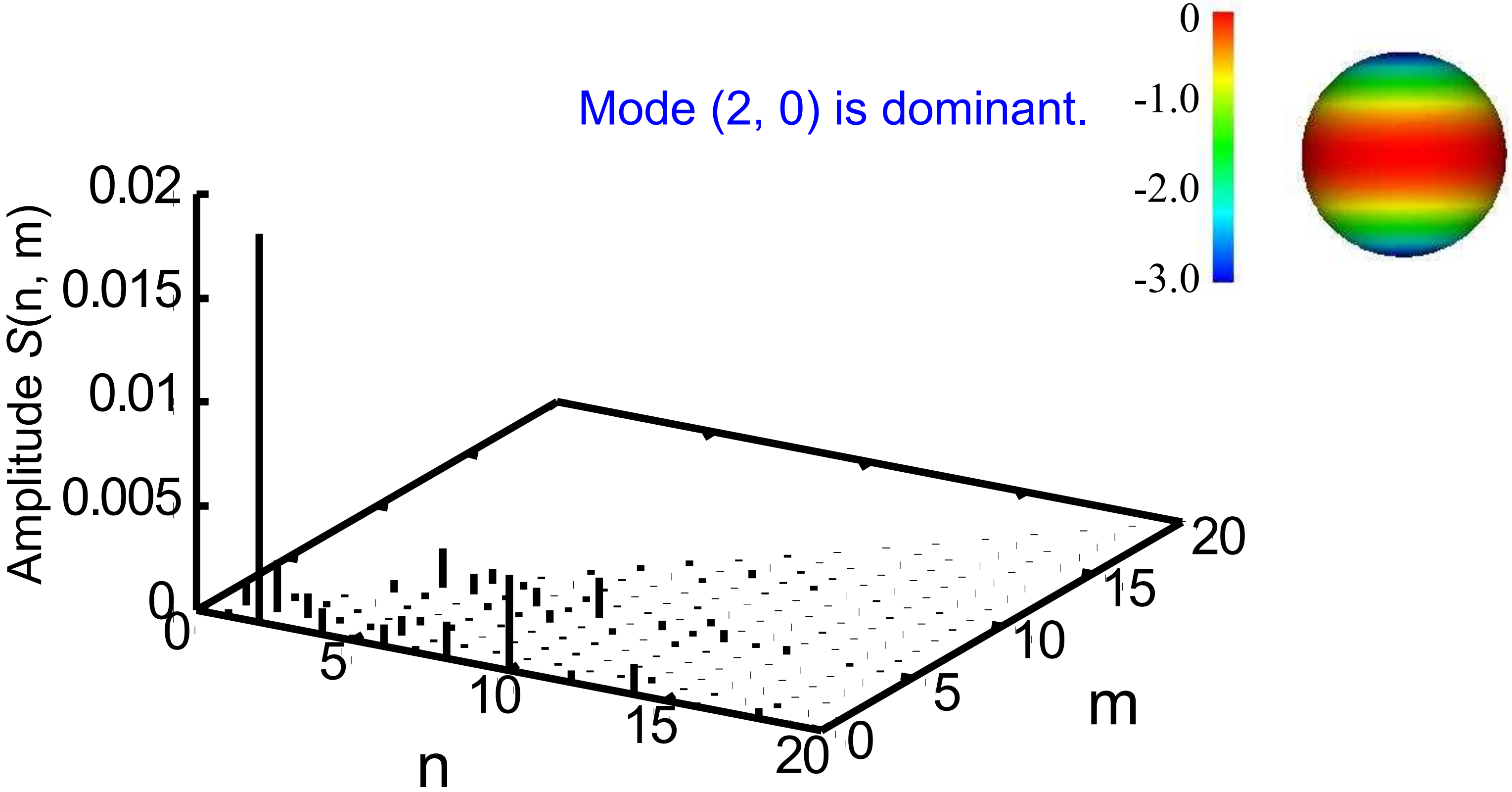




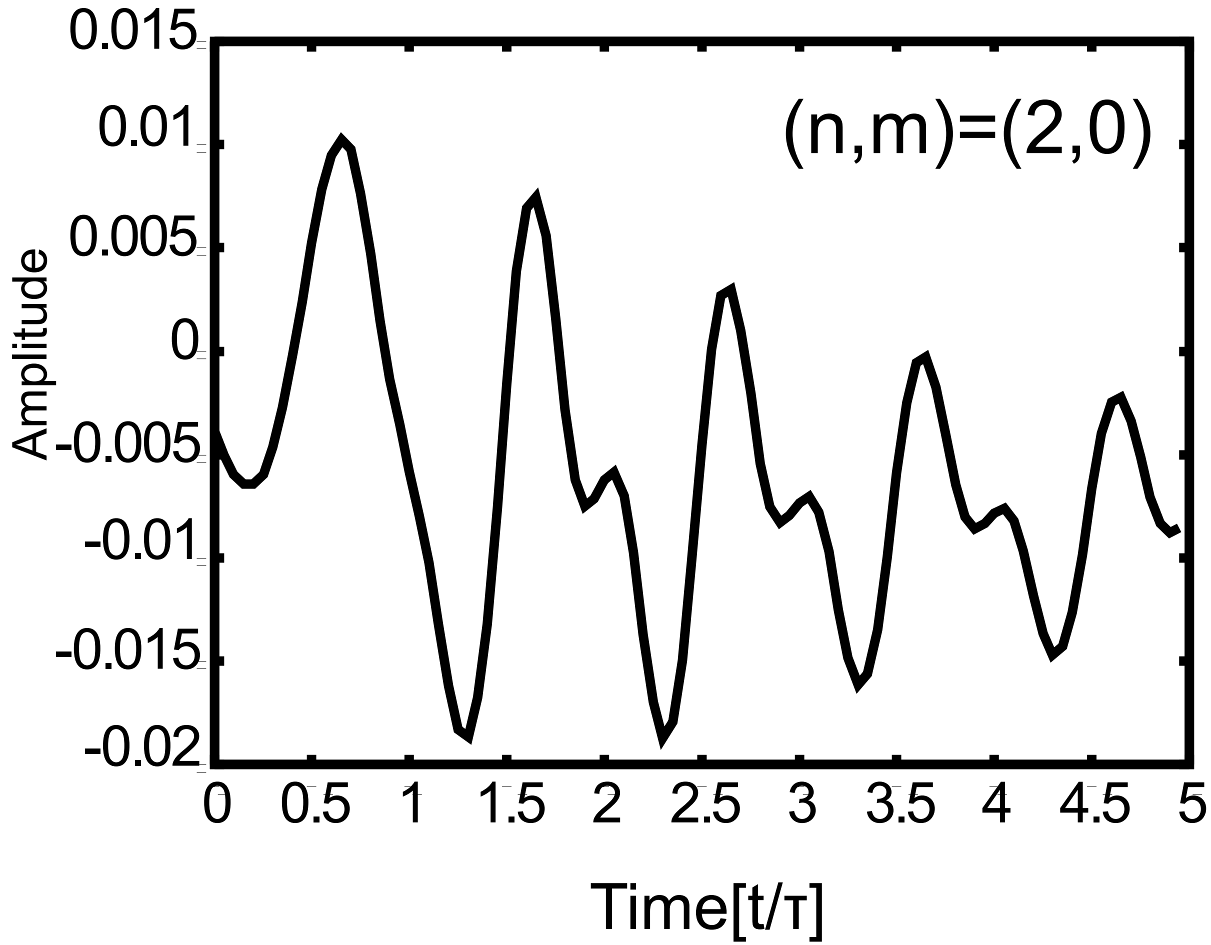




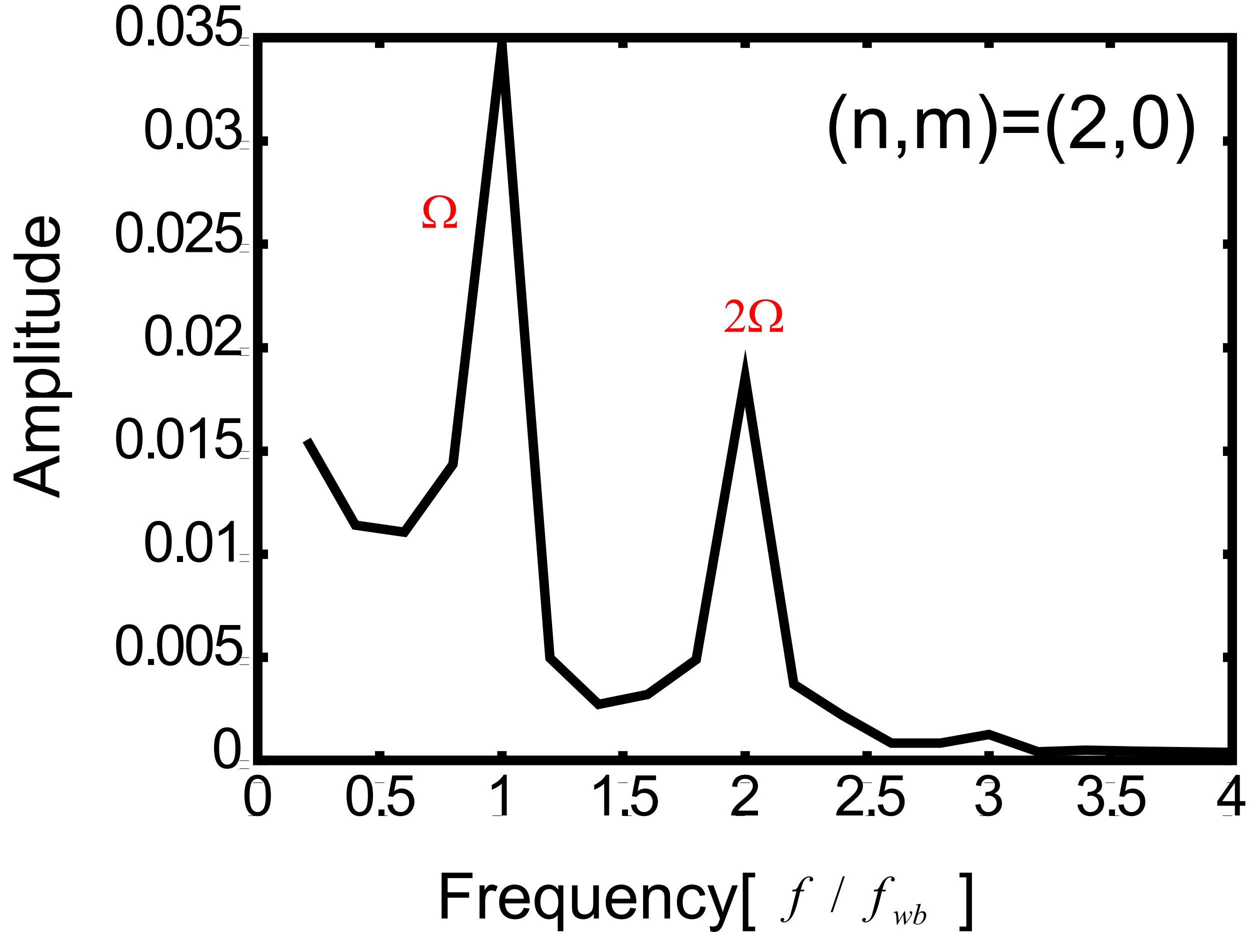
RMS
Energy loss
Non-uniformity (RMS) [%]
Energy loss[%]
Time[t/τ]
0
0.5
1
1.5
2
2.5
3
3.5
4
0
2
4
6
8
10
12
14
0
1
2
3
4
5
6
7
8
9
10



Mode (2, 0) is dominant.
0
-1.0
-2.0
-3.0
Amplitude S(n, m)
0.02
0.015
0.01
0.005
0
0
5
10
15
20
n
0
5
10
15
20
m


(n,m)=(2,0)
Amplitude
Time[t/τ]
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5

A few % of energy deposition nonuniformity oscillates with the the wobbling HIBS oscillation frequency Ω.



Summary

/ Spiral Wobbling HIBs introduce
a low illumination non-uniformity. < 3.8%

/ Initial imprint does not give a large nonuniformity.

HIB main pulse ~ 10 - 20 nsec
Rotation frequency ~ several 100MHz~1GHz
=>
We found a time-dependent wobbling HIBs illumination
with a sufficient uniformity
+ with a time-dependent small nonuniformity
with the the wobblers oscillation frequency Ω.
-> may induces $g=g_0+\delta g$
-> Wobbling HIBs may give a new smoothing & R-T growth mitigation method!