Laser and Particle Beams (2016), *34*, 729–734.

doi:10.1017/S0263034616000677

Control of fuel target implosion non-uniformity in heavy ion inertial fusion

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(RECEIVED 29 July 2016; ACCEPTED 17 September 2016)

Abstract

In inertial fusion, one of scientific issues is to reduce an implosion non-uniformity of a spherical fuel target. The implosion non-uniformity is caused by several factors, including the driver beam illumination non-uniformity, the Rayleigh–Taylor instability (RTI) growth, etc. In this paper, we propose a new control method to reduce the implosion non-uniformity; the oscillating implosion acceleration $\delta g(t)$ is created by pulsating and dephasing heavy-ion beams (HIBs) in heavy-ion inertial fusion (HIF). The $\delta g(t)$ would reduce the RTI growth effectively. The original concept of the non-uniformity control in inertial fusion was proposed in [*Laser Part. Beams* (1993) **11**, 757–768]. In this paper, it was found that the pulsating and dephasing HIBs illumination provide successfully the controlled $\delta g(t)$ and that $\delta g(t)$ induced by the pulsating HIBs reduces well the implosion non-uniformity. Consequently the pulsating HIBs improve a pellet gain remarkably in HIF.

Keywords: Heavy ion inertial fusion; Target implosion; Dynamic stabilization; Wobbling beam

1. INTRODUCTION

A heavy-ion beam (HIB) has preferable features to release the fusion energy in inertial fusion: in particle accelerators HIBs are generated with a high driver efficiency of ~30–40%, and the HIB ions deposit their energy inside of materials. Therefore, a requirement for the fusion target energy gain is relatively low, that would be ~50 to operate a HIF fusion reactor with the standard energy output of 1 GW of electricity (Kawata *et al.*, 2016). Key issues in heavy-ion inertial fusion (HIF) include a target implosion uniformity to obtain a sufficient fusion energy output. The requirement for the implosion uniformity is very stringent, and the implosion non-uniformity must be less than a few % (Emery *et al.*, 1982; Kawata & Niu, 1984; Kawata & Karino, 2015; Kawata *et al.*, 2016). Therefore, it is essentially important to improve the fuel target implosion uniformity. The target implosion should be robust against the implosion non-uniformities for the stable reactor operation. In general, the target implosion non-uniformity is introduced by the driver beams' illumination non-uniformity, an imperfect target sphericity, a non-uniform target density, a target alignment error in a fusion reactor, etc. To reduce the non-uniformity, we have focused on the Rayleigh–Taylor instability(RTI) (Wolf, 1970; Troyon & Gruber, 1971; Boris, 1977; Betti *et al.*, 1993; Piriz *et al.*, 2010, 2011; Kawata, 2012; Kawata & Karino, 2015): by an additional oscillating acceleration δg, the RTI growth is mitigated and the RTI perturbation growth is significantly reduced. In this paper, we propose to realize the mitigation mechanism by pulsating and dephasing HIBs in the HIB target implosion. Each HIB has its pulsating phase depending on the HIB axis position in order to produce the global controlled δg to mitigate the implosion non-uniformity. Our fluid implosion simulations demonstrate that the implosion acceleration is successfully modulated by the pulsating and dephasing HIBs' illumination, and the controlled δg was created during the target implosion.

2. NON-UNIFORMITY MITIGATION METHOD

In this study, we analyze the implosion non-uniformity by the arbitrary Lagrangian–Eulerian method hydrodynamics simulation (Hirt *et al.*, 1974). The target structure is shown in Figure 1. The 32 Pb^+ ion beams are illuminated in the arrangement shown in Figure 2 to the target (Skupsky & Lee,

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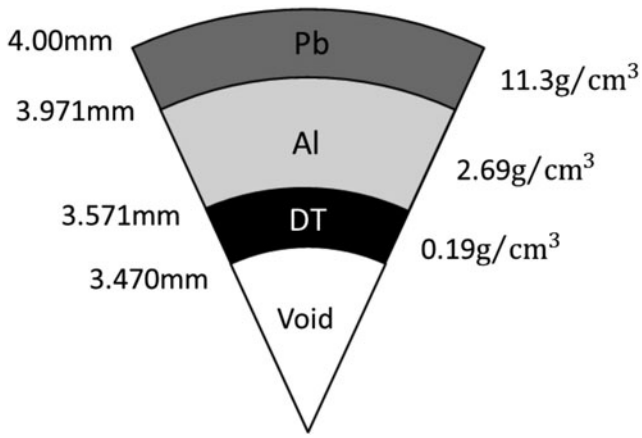

Fig. 1. Target structure.

1983; Ogoyski *et al.*, 2004, 2010). The HIB particle density has the Gaussian distribution, and the transverse beam emittance is 3.2 mm-mrad.

When the instability driver wobbles uniformly in time, the imposed perturbation $\delta g(t)$ for a gravity g_0 at $t = \tau$ may be written as

$$g = g_0 + \delta g(t) = g_0 + \delta g e^{i\Omega\tau} e^{\gamma(t-\tau)+i\vec{k}\cdot\vec{x}}. \quad (1)$$

Here, δg is the amplitude, Ω is the wobbling or oscillation frequency defined actively by the dribing wobbler, and $\Omega\tau$ is the phase shift of superimposed perturbations. At each time t, the wobbler or the modulated driver provides a new perturbation with the phase and the amplitude actively defined by the driving wobbler itself. The superposition of the perturbations provides the actual perturbation at t as follows:

$$\int_0^t d\tau \delta g e^{i\Omega\tau} e^{\gamma(t-\tau)+i\vec{k}\cdot\vec{x}} \propto \frac{\gamma + i\Omega}{\gamma^2 + \Omega^2} \delta g e^{\gamma t} e^{i\vec{k}\cdot\vec{x}}. \quad (2)$$

When $\Omega \gg \gamma$, the perturbation amplitude is reduced by the factor of γ/Ω, compared with the pure instability growth ($\Omega = 0$) based on the energy deposition non-uniformity. The result in Eq. (2) presents that the perturbation phase should oscillate with $\Omega \gtrsim \gamma$ for the effective amplitude reduction.

In the simulations, we realize the oscillating δg and the mitigation mechanism by the following pulsating foot and main HIB pulses. The foot pulse power P_{foot} and the main pulse power P_{main} (see Fig. 3) are represented by the following equations:

$$P_{\text{foot}} = 5.80[\text{TW}]\left(1 + A\sin\left(\frac{2\pi t}{T} + \frac{2\pi\xi}{360}\right)\right), \quad (3)$$

$$P_{\text{main}} = 320[\text{TW}]\left(1 + A\sin\left(\frac{2\pi t}{T} + \frac{2\pi\xi}{360}\right)\right). \quad (4)$$

Here A is the amplitude of the input pulse, T is the pulsation period and ξ is the phase of each pulsating HIB. In this case, we employ $A = 0.100$ and $T = 1.00$ ns for our simulations. The phase ξ for each HIB is listed in Table 1.

3. EVALUATION METHOD FOR NON-UNIFORMITY

In this study, we use the root mean square (RMS) shown by the following equation for the non-uniformity evaluation:

$$\sigma_i^{\text{rms}} = \frac{1}{F}\sqrt{\frac{\sum_j (F_{ij} - F_{ij})^2}{\theta_{\text{mesh}}}}. \quad (5)$$

F_{ij} is a physical quantity, $\langle F_{ij}\rangle$ is the average of physical quantity of circumferential direction on a certain radius, θ_{mesh} is the total mesh number in the θ-direction, and (i, j) is the mesh numbers for the radial direction and the azimuthal direction, respectively.

We also perform the mode analysis for the non-uniformity $f(\theta)$ based on the Legendre polynomial P_n. Here the

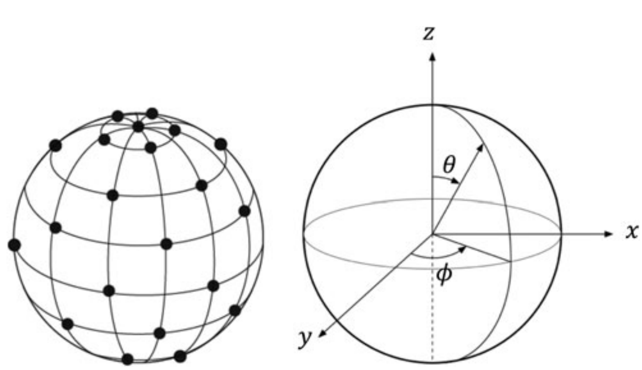

Fig. 2. 32HIBs system.

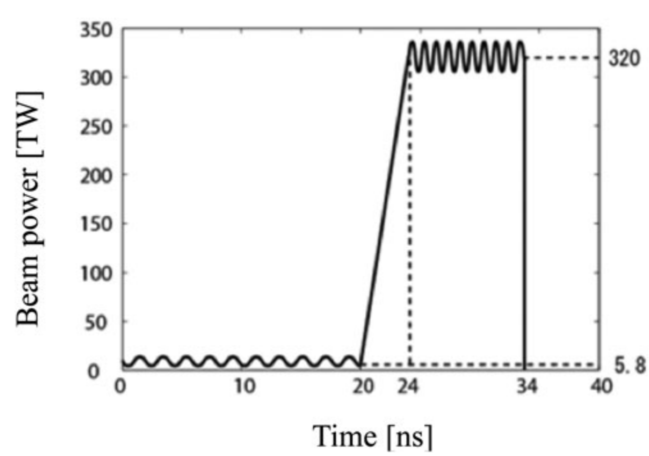

Fig. 3. Beam power pulsation.

https://doi.org/10.1017/S0263034616000677 Published online by Cambridge University Press

Table 1. *Beam power phase ξ for each HIB.*

θ (°)	ϕ (°)	ξ (°)	θ (°)	ϕ (°)	ξ (°)
0.000	0.000	0.000	100.812	36.000	205.714
37.377	0.000	51.429	100.812	108.000	277.714
37.377	72.000	123.429	100.812	180.000	349.714
37.377	144.000	195.429	100.812	252.000	61.714
37.377	216.000	267.429	100.812	324.000	133.714
37.377	288.000	339.429	116.565	0.000	257.714
63.435	36.000	102.857	116.565	72.000	329.143
63.435	108.000	174.857	116.565	144.000	41.143
63.435	180.000	246.857	116.565	216.000	113.143
63.435	252.000	318.857	116.565	288.000	185.143
63.435	324.000	30.857	142.623	36.000	308.571
79.188	0.000	154.286	142.623	108.000	20.571
79.188	72.000	226.286	142.623	180.000	92.571
79.188	144.000	298.286	142.623	252.000	164.571
79.188	216.000	10.286	142.623	324.000	236.571
79.188	288.000	82.286	180.000	0.000	0.000

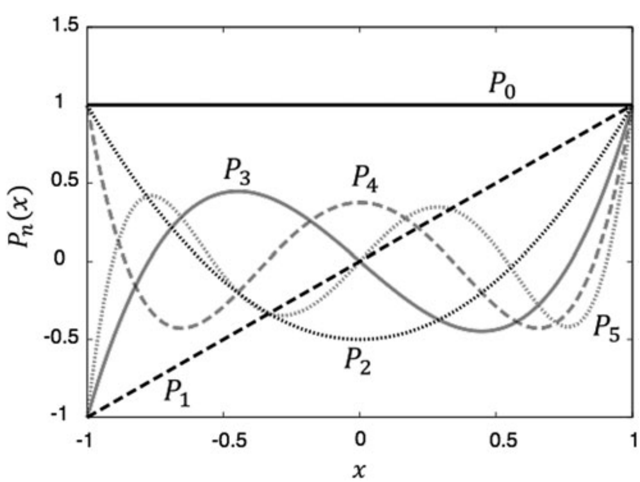

Fig. 4. Legendre polynomial $P_n(P_0 \sim P_5)$.

amplitude of the mode n is obtained by the following equation:

$$A_n = \frac{2n+1}{2}\int_0^{\pi} f(\cos\theta)P_n(\cos\theta)\sin\theta d\theta. \quad (6)$$

The Legendre polynomial $P_n(P_0 \sim P_5)$ is shown in Figure 4 for reference.

4. NON-UNIFORMITY MITIGATION IN HIF TARGET IMPLOSION

First, we examine the effect of the pulsating and dephasing HIBs illumination on the target implosion acceleration. Figures 5 shows the implosion acceleration histories at θ = 0°, 74.6°, and 152° for the deuterium and tritium (DT) layer. In Figure 5a, the pulsating HIBs are in phase, and so the implosion acceleration is also in phase. However, in Figure 5b the pulsating HIBs' phases are controlled as shown in Table 1. Figure 5b demonstrates that the pulsating and controlled dephasing HIBs illumination creates the DT fuel implosion acceleration oscillation of δg.

Table 2 shows the summary of the implosion simulation results for the in-phase HIBs illumination and for the dephasing HIBs.

Figure 6 shows the non-uniformity histories of the density ρ, the ion temperature T_i, the pressure P and the radial direction speed V_r of the DT layer. The solid line shows the non-uniformities by the in-phase HIBs' illumination, and the dotted line shows them by the dephasing pulsating HIBs' illumination. Figure 6 presents that the dephasing and pulsating HIBs reduce the non-uniformities successfully.

Figures 7a, 7b show the non-uniformity mode analyses results for the averaged ion temperature T_i of the DT layer at $t = 38$ ns). Figure 7 presents that the dephasing and pulsating HIBs reduce the largest mode of the "Mode 2" significantly.

In Table 1, and Figures 5, 6, and 7b, the oscillation amplitude A of the HIBs input power in Eqs (3) and (4) was $A = 0.100$. Figure 8 shows the relation of the fuel target gain versus the oscillation amplitude A of the HIBs input power.

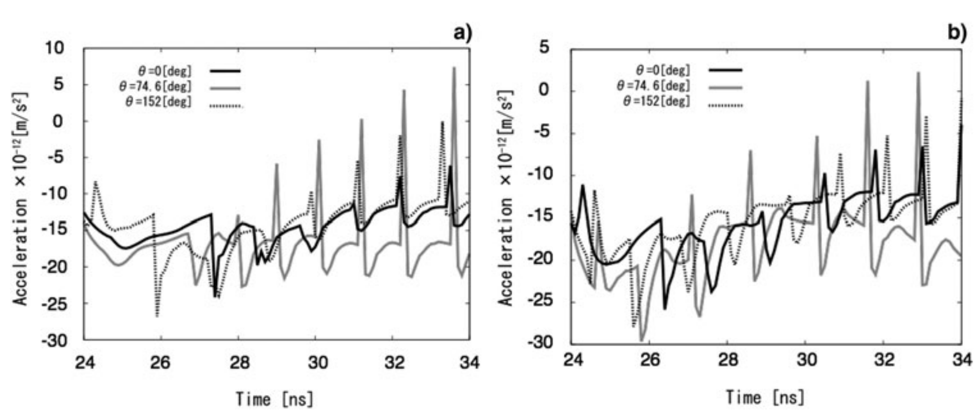

Fig. 5. Time histories of the DT fuel acceleration. (a) In-phase HIBs illumination. (b) Dephasing HIBs illumination.

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Table 2. *Implosion result summary for the in-phase HIBs and for the dephasing HIBs.*

	In-phase HIBs	Dephasing HIBs (A = 0.100)
Void close time (ns)	38.9	38.2
Gain	38.7	50.8
Max ρ (kg/m^3)	21,800	21,900
Max T_i (KeV)	9.23	8.48

When the HIBs input power oscillation of A is 0.1, the fuel target gain becomes the maximum. The target gain becomes 0, when A exceeds 0.140. The results in Figure 8 demonstrate that the dephasing and pulsating HIBs illumination realizes the better uniformity in the DT fuel implosion, and consequently leads a higher gain.

We also study the robustness against the displacement dz (see Fig. 9) of the target misalignment in a fusion reactor. Figure 10 shows the relation between the fuel target gain

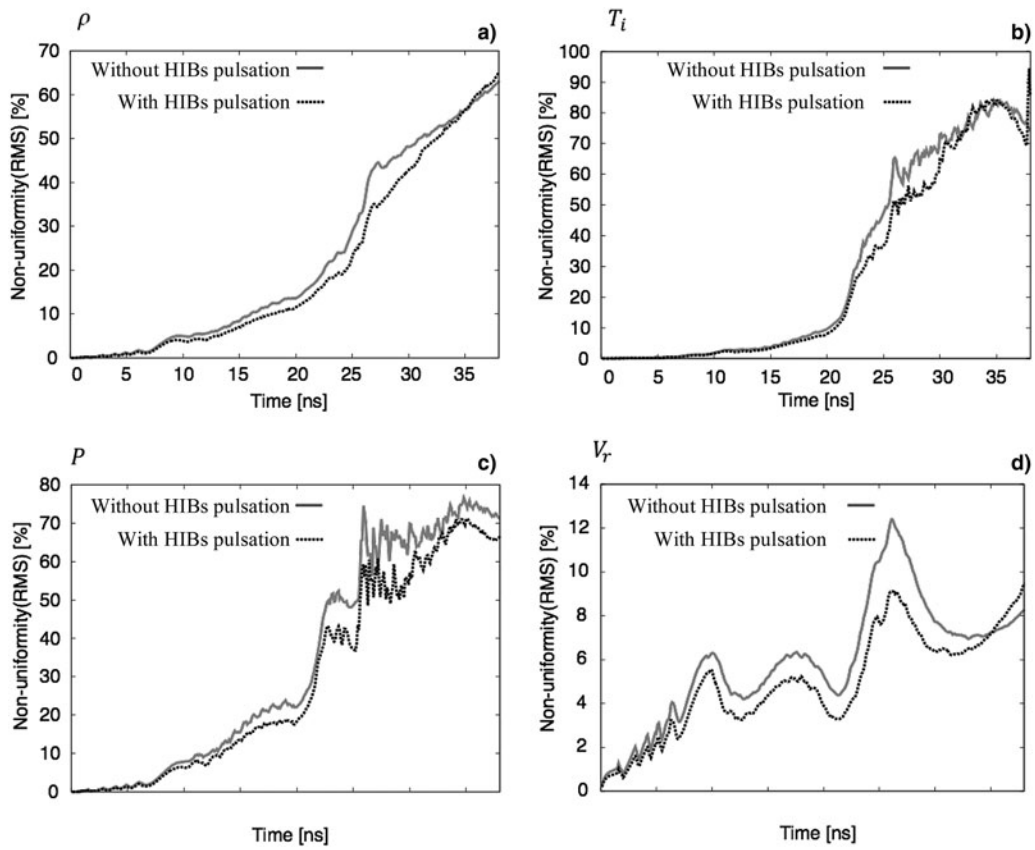

Fig. 6. Time histories of the DT fuel non-uniformities for the pulsating and dephasing HIBs and for the HIBs without the pulsation.

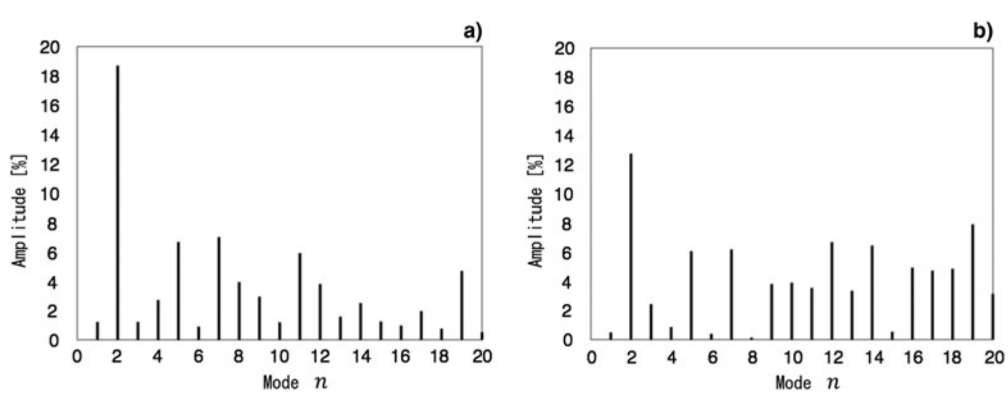

Fig. 7. Modes of the ion temperature T_i in the DT layer at t = 38 ns. (a) W/o HIBs pulsation and (b) with HIBs pulsation.

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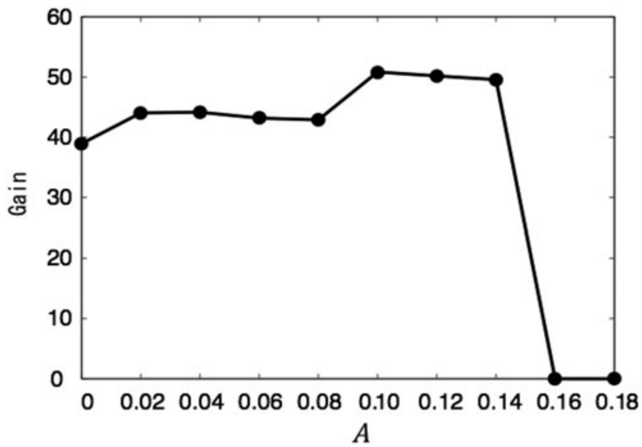

Fig. 8. Target fuel gain versus the HIBs pulsating amplitude *A*.

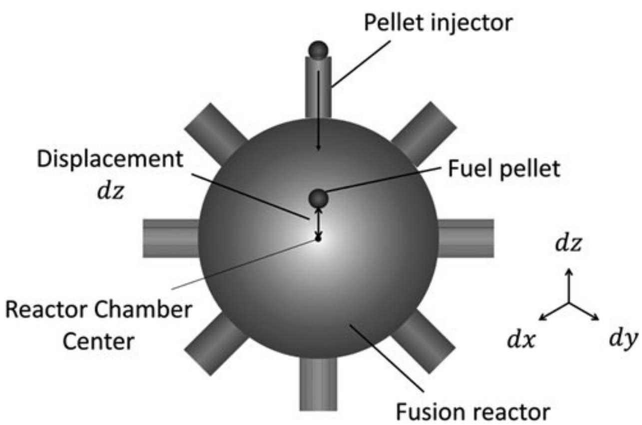

Fig. 9. Target displacement *dz*.

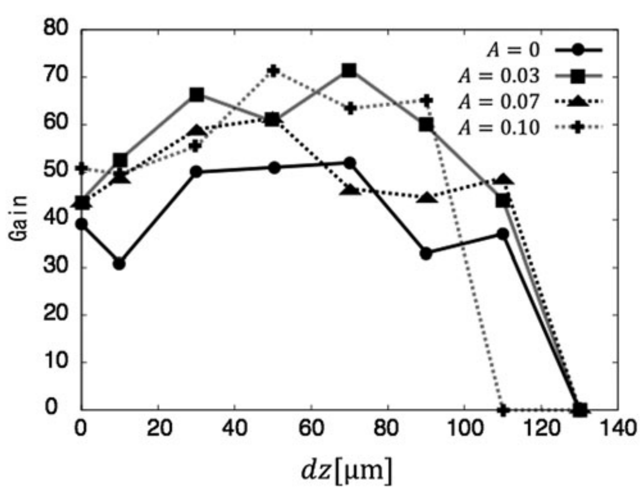

Fig. 10. Gain versus the target misalignment *dz*.

and the displacement *dz* for each input pulse modulation amplitude *A*. Figure 10 presents that the dephasing and pulsating HIBs illumination is robust against the target misalignment *dz*. When *dz* increases, the implosion non-uniformity increases (Kawata *et al.*, 2016). Therefore, the relatively larger *dz* does not induce the fuel ignition, and for the larger *dz* no fusion output energy is obtained as shown in Figure 10. The gain curve tendency in Figure 10 should be studied further in the near future.

5. CONCLUSIONS

In this paper, we have shown that the pulsating and dephasing HIBs illumination creates the oscillating acceleration δg, which mitigates the RTI growth. In our previous works (Kawata *et al.*, 1993; Kawata, 2012; Kawata & Karino, 2015), it was demonstrated that the oscillating acceleration δg reduces the instability growth significantly. The pulsating HIBs illumination onto a fuel target induces the oscillating δg successfully. It was found that the target material responds to the deposited HIBs pulsation directly. In this paper, the pulsating HIBs phases are designed as shown in Table 1 to create the large wave mode of P_2 or so, so that the RTI growth rate would be also minimized. The work presented in this paper demonstrates that the controlled HIBs illumination provides a useful tool to realize a stable and uniform implosion in HIF.

ACKNOWLEDGMENTS

The work was partly supported by JSPS, MEXT, CORE (Center for Optical Research and Education, Utsunomiya University), ILE/Osaka University, and CDI (Creative Department for Innovation, Utsunomiya University). The authors also would like to extend their acknowledgements to friends in HIF research group in Japan, in Tokyo Institute of Technology, Nagaoka University of Technology, KEK and also in HIF-VNL, USA.

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