ISSN 0915-633X

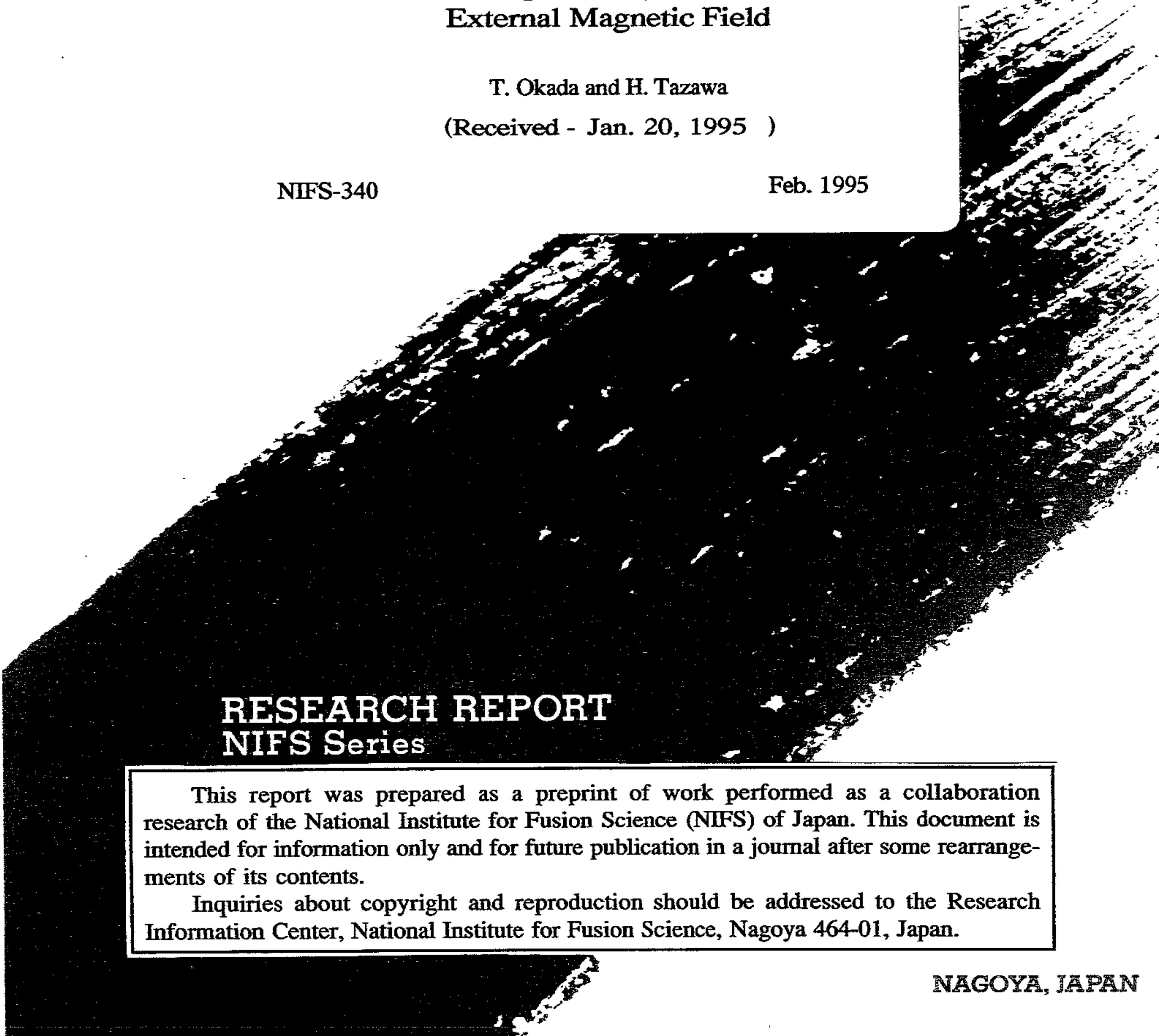
NATIONAL INSTITUTE FOR FUSION SCIENCE

Filamentation Instability in a Light Ion Beam-plasma System with External Magnetic Field

T. Okada and H. Tazawa

(Received - Jan. 20, 1995)

NIFS-340 Feb. 1995



RESEARCH REPORT
NIFS Series

NAGOYA, JAPAN

FILAMENTATION INSTABILITY IN A LIGHT ION BEAM-PLASMA SYSTEM WITH EXTERNAL MAGNETIC FIELD

T. OKADA AND H. TAZAWA

Tokyo University of Agriculture and Technology
Naka-machi, Koganei-shi, Tokyo 184, Japan

Abstract

The filamentation instability for a light ion beam (LIB) penetrating plasma is investigated. For the stabilization of the filamentation instability, an external magnetic field which is parallel to the direction of the light ion beam propagation is applied. From a dispersion relation, linear growth rates of filamentation instabilities are obtained in a light ion beam-plasma system with an external magnetic field. Numerical simulations are carried out using a particle-in-cell (PIC) method. The stabilizing mechanism of the filamentation instability is described. The theory and simulation comparisons illustrate the results.

Keywords: Filamentation Instability, Inertial Confinement Fusion, Light Ion Beam (LIB) Propagation, Particle-in-cell (PIC) Simulation

In the investigation of the inertial confinement fusion by LIB [1-3], it is the central problem to propagate the beam stably through the plasma. There are many investigations of numerous instabilities in relativistic electron beam [4], heavy ion beam [5] and light ion beam [6,7] propagations. Filamentation instability [8] is one of the instabilities which is deleterious in the stable propagation of the beam through the plasma. The rotating light ion beam scheme [9] has been proposed for the stable propagation of the beam. We have theoretically reported the stability of the filamentation instability by the application of the external magnetic field which is induced by the rotating ion beams [10]. In this paper, we report on numerical studies of the stabilization of filamentation instability in a light ion beam-plasma system with an external magnetic field. In this paper, we only consider the model of spatially infinite collisionless, charge, and current neutral system with light ion beam propagation velocity $\boldsymbol{V}_{zb}$ and background plasma at $\boldsymbol{V}_{zs}$ of species $s = e$ (plasma electrons) or i (plasma ions) along $\boldsymbol{B}_0^z$ which is an external magnetic field in the z-direction. We only consider electromagnetic modes with $\boldsymbol{k}_\perp$ normal to $\boldsymbol{V}_{zb}$, induced electric fields $\delta\boldsymbol{E}$ parallel to $\boldsymbol{V}_{zb}$ and induced magnetic fields $\delta\boldsymbol{B}$ normal to both $\boldsymbol{V}_{zb}$ and $\delta\boldsymbol{E}$. The dispersion relation for the filamentation instability has been investigated for a beam-plasma system with external magnetic field. For a monoenergetic beam with Maxwellian thermal spread v_{Tb} of transverse velocities, and a background plasma with a Maxwellian thermal spread v_{Ts} (s=e,i), assuming that the ion beam density n_b is smaller than the background electron density n_e, the relativistic linear dispersion relation is given by [11]

$$\omega^2 = c^2k_\perp^2 + \sum_{j=b,e,i}\omega_{pj}^2 + \sum_{j=b,e,i}\omega_{pj}^2\frac{\beta_j^2c^2k_\perp^2}{\omega^2-\omega_{cj}^2}. \qquad (1)$$

where $\omega_{pj}^2 = 4\pi n_j e_j^2/m_j$, $\omega_{cj} = |e_j|B_0^z/m_jc$ and $\beta_j c = V_{zj}$.

From Eq.(1), we expect that the maximum growth rate of the filamentation instability is stabilized by the external magnetic field and the beams can propagate without triggerring the filamentation instability or with having sufficiently slow filamentation growth.

In order to simulate a filamentation instability, we perform a numerical calculation using an electromagnetic particle in-cell code [12] for the beam-plasma system. The code is two-dimensional in space and velocity, respectively. The external magnetic field B_0^z is in the z-direction and the induced electric and magnetic fields are respectively indicated by $E = (0, 0, E_z)$ and $B = (B_x, B_y, 0)$. The simulation is performed under the conditions that the grid spacing is $0.2c/\omega_{pe}$, the time step is $0.1\omega_{pe}^{-1}$, the length of simulation range is $3.2c/\omega_{pe}$, the number of ion beam simulation particles is 2500, the number of plasma electron simulation particles is 7500, and the number of plasma ion simulation particles is 5000. We choose the following parameters (ensuring current neutrality); $v_{Tb} = \sqrt{T_b/m_b} = 0.001c$, $v_{Tj} = \sqrt{T_j/m_j} = 0.01c$ $(j = e, i)$, $V_{zb} = 0.1c$ and $V_{ze} = 1/30c, V_{zi} = 0$. The induced magnetic fields for $B_0^z/(4\pi n_e m_e c^2)^{1/2}$ =0 are plotted in Fig.1, from which we can estimate that the maximum growth rate γ_S is about $7.1\times10^{-3}\omega_{pe}$. This growth rate is fairly consistent with $(Im\ \omega)_{max} \approx 6.4\times10^{-3}\omega_{pe}$ which is solved in Eq.(1). The induced magnetic fields for $B_0^z/(4\pi n_e m_e c^2)^{1/2}$ =0.02 are plotted in Fig.1, from which we can estimate that the maximum growth rate γ_S is about $5.6\times10^{-3}\omega_{pe}$. This growth rate is fairly consistent with $(Im\ \omega)_{max} \approx 2.4\times10^{-3}\omega_{pe}$ which is solved in Eq.(1). The induced magnetic fields for $B_0^z/(4\pi n_e m_e c^2)^{1/2}$ =0.2 are plotted in Fig.1, from which we can estimate that the maximum growth rate γ_S is about $8.0\times10^{-6}\omega_{pe}$. We obtain the growth rate $(Im\ \omega)_{max} \approx 1.2\times10^{-4}\omega_{pe}$ from Eq.(1). There is a disagreement between the growth rates in the theory and simulations because the theory is in cylindrical symmetric coordinates and simulation is in cartesian coordinates. In Fig.2,the maximum growth rates, which are obtained by using the PIC code are plotted versus the external magnetic field B_0^z. In Fig.3, the beam kinetic energies are plotted versus the time, being separated for external magnetic fields. From these results, the filamentation instability is stabilized by the external magnetic fields. The three dimensional PIC simulations will be reported in a future work.

We will discuss the results for an expected experiment, i.e. for a typical beam of 5MeV (V_b=0.1c) protons,well-pinched ion current of 0.5MA ($n_b = 10^{15}cm^{-3}$) and

40nsec beam duration τ. If we apply an external magnetic field $B_0^z=0.2(4\pi n_e m_e c^2)^{1/2} \approx$ 3.5tesla ($n_e=3\times 10^{15} cm^{-3}$) to the beam-plasma system. the maximum growth rates of the filamentation instability become $\gamma_S=8.0\times 10^{-6}\omega_{pe} \approx 2.5 \times 10^7 sec^{-1}$ as seen in Fig.2. The largest growth will appear at the tailend of the beam. we estimate the effect at the tailend to be the value of $\gamma_S\tau$. Consequently. the beams can propagate stably through the plasma by the external magnetic fields with a small growth rate since $\gamma_S\tau=0.98$ which is small e-foldings.

To simplify the stabilization mechanism of the filamentation instability by applying the external magnetic field, we limit ourselves to a one-dimensional configuration. The beam is in the z-direction. If there is no external magnetic field. the induced magnetic field bends the orbits of beam ions. and collects ions in its neutral points. The perturbed current amplifies the induced magnetic field. On the other hand,the external magnetic field parallel to the beam direction prevents bending the orbits of beam ions. Consequently. the filamentation instability may be stabilized by the external magnetic field.

This work was carried out under the collaborating research program at the National Institute for Fusion Science of Japan.

References

[1] C.L.Olson, J. Fusion Energy **1**, 309 (1982).

[2] J.P.VanDevender and D.L.Cook, Science **232**. 831 (1986).

[3] D.L.Cook, Bull. of American Phys. Soc., **36**, 2480 (1991).

[4] R.Lee and M.Lampe, Phys. Rev. Lett. **31**. 1390 (1973).

[5] S.Jorna and W.B.Thompson, J. Plasma Physics **19**, 97 (1978).

[6] P.F.Ottinger, D.Mosher and S.A.Goldstein. Phys. of Fluids **24**, 164 (1981).

[7] T.Okada and W.Schmidt, J. Plasma Physics **37**, 373 (1987).

[8] C.L.Olson (private communication).

[9] K.Niu, Laser and Particle Beams **12**, 85 (1994).

[10] T.Okada and K.Niu, Laser and Particle Beams **6**, 699 (1988).

[11] R.C.Davidson, *Basic Plasma Physics* **2**, edited by A.A.Galeev and R.N.Sudan (North-Holland, Amsterdam, 1984).

[12] R.L.Morse, *Methods in Computational Physics* **9**, 213 (Academic Press, New York, 1970).

Figure Captions

FIG. 1. Energies of induced magnetic fields at the linear stage with (a)$B_0^z/(4\pi n_e m_e c^2)^{1/2}$ =0, (b)$B_0^z/(4\pi n_e m_e c^2)^{1/2}$ =0.02 and (c)$B_0^z/(4\pi n_e m_e c^2)^{1/2}$ =0.2.

FIG. 2. Maximum growth rates of the filamentation instability versus the external magnetic fields. Circles represent results as obtained by using PIC simulation code.

FIG. 3. Beam kinetic energies with (a)$B_0^z/(4\pi n_e m_e c^2)^{1/2}$ =0, (b)$B_0^z/(4\pi n_e m_e c^2)^{1/2}$ =0.02 and (c)$B_0^z/(4\pi n_e m_e c^2)^{1/2}$ =0.2.

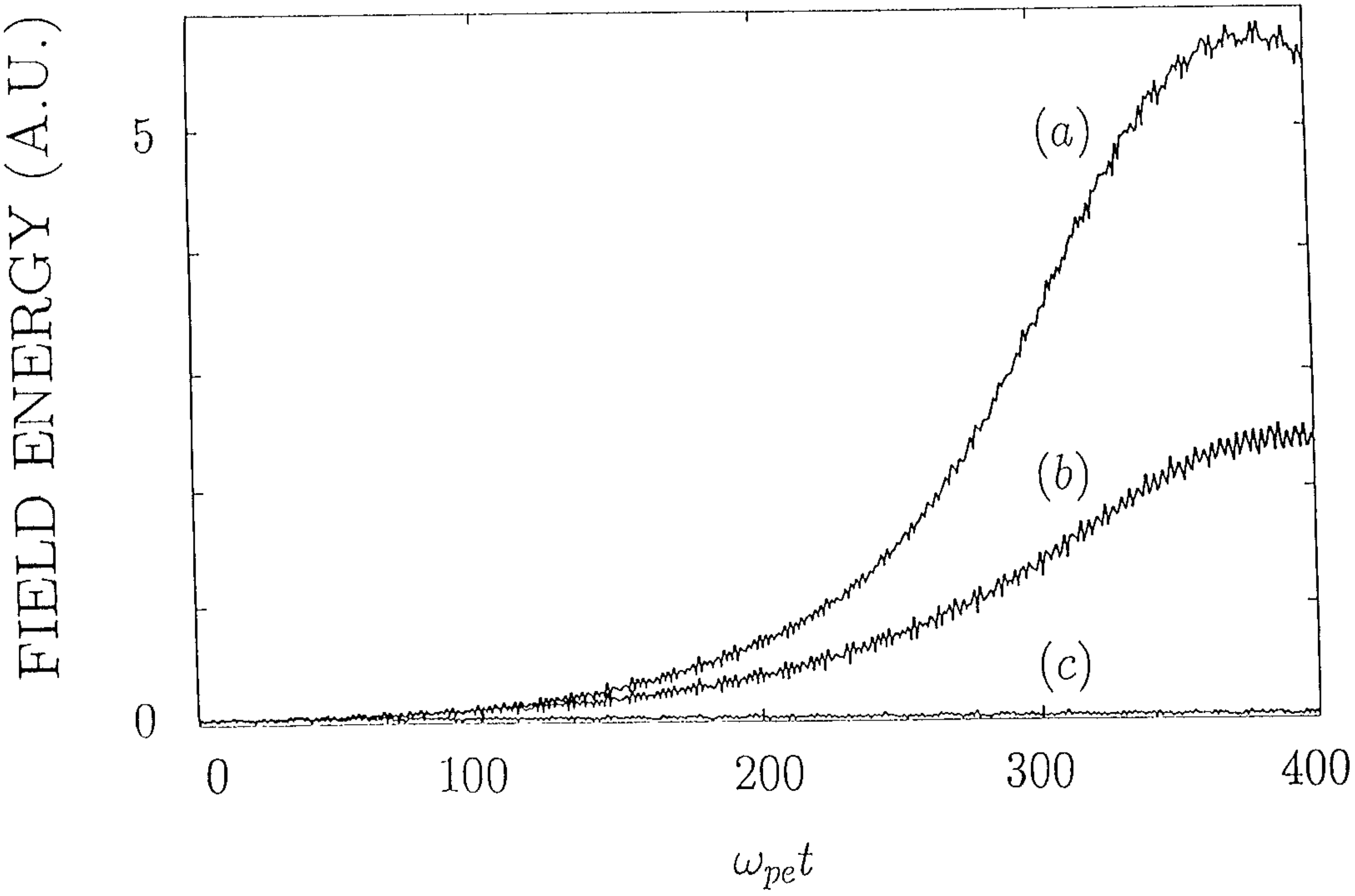


Fig.1

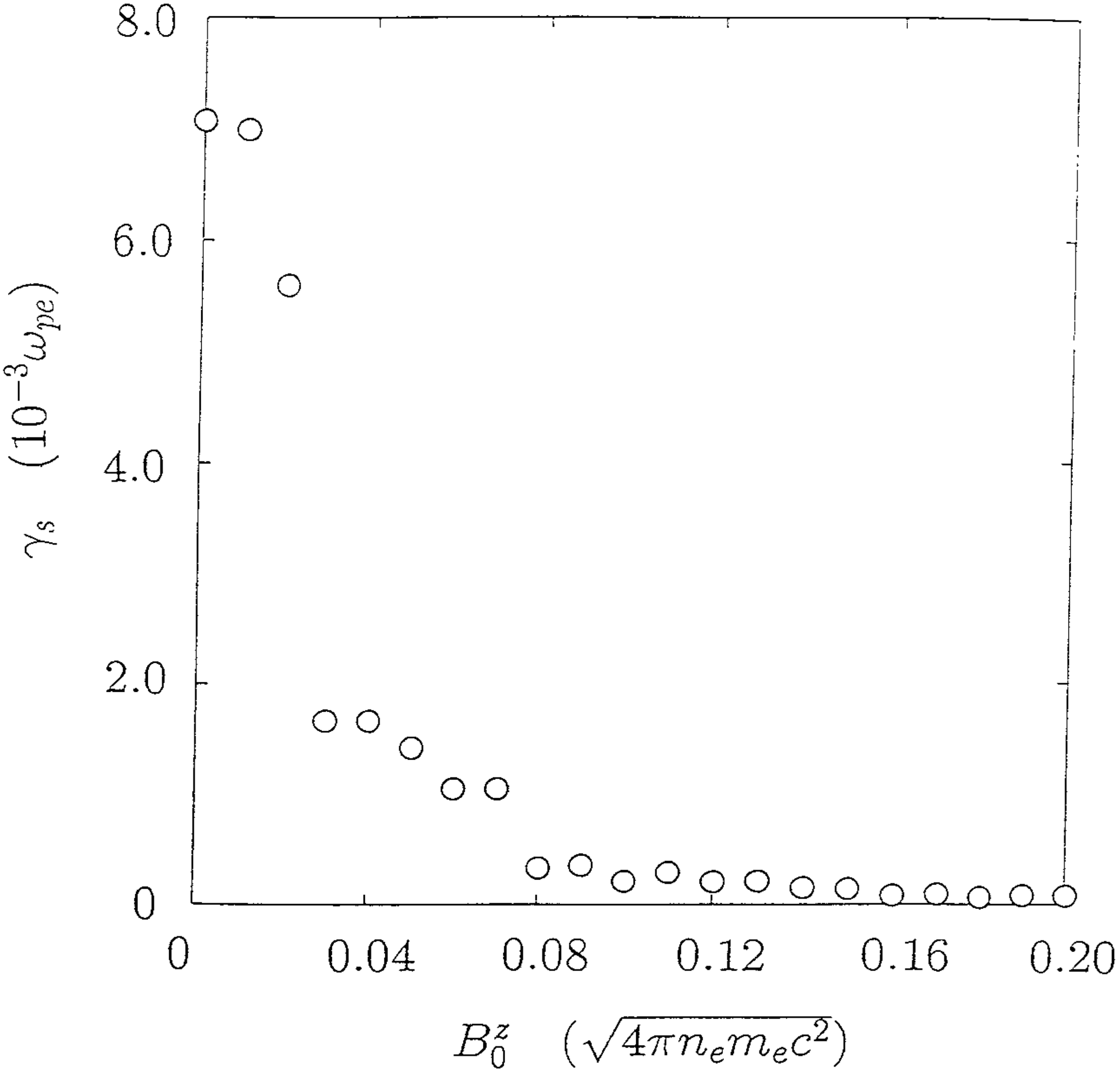

8.0
6.0
4.0
2.0
0
γ_s $(10^{-3}\omega_{pe})$
0
0.04
0.08
0.12
0.16
0.20
B_0^z $(\sqrt{4\pi n_e m_e c^2})$

Fig.2

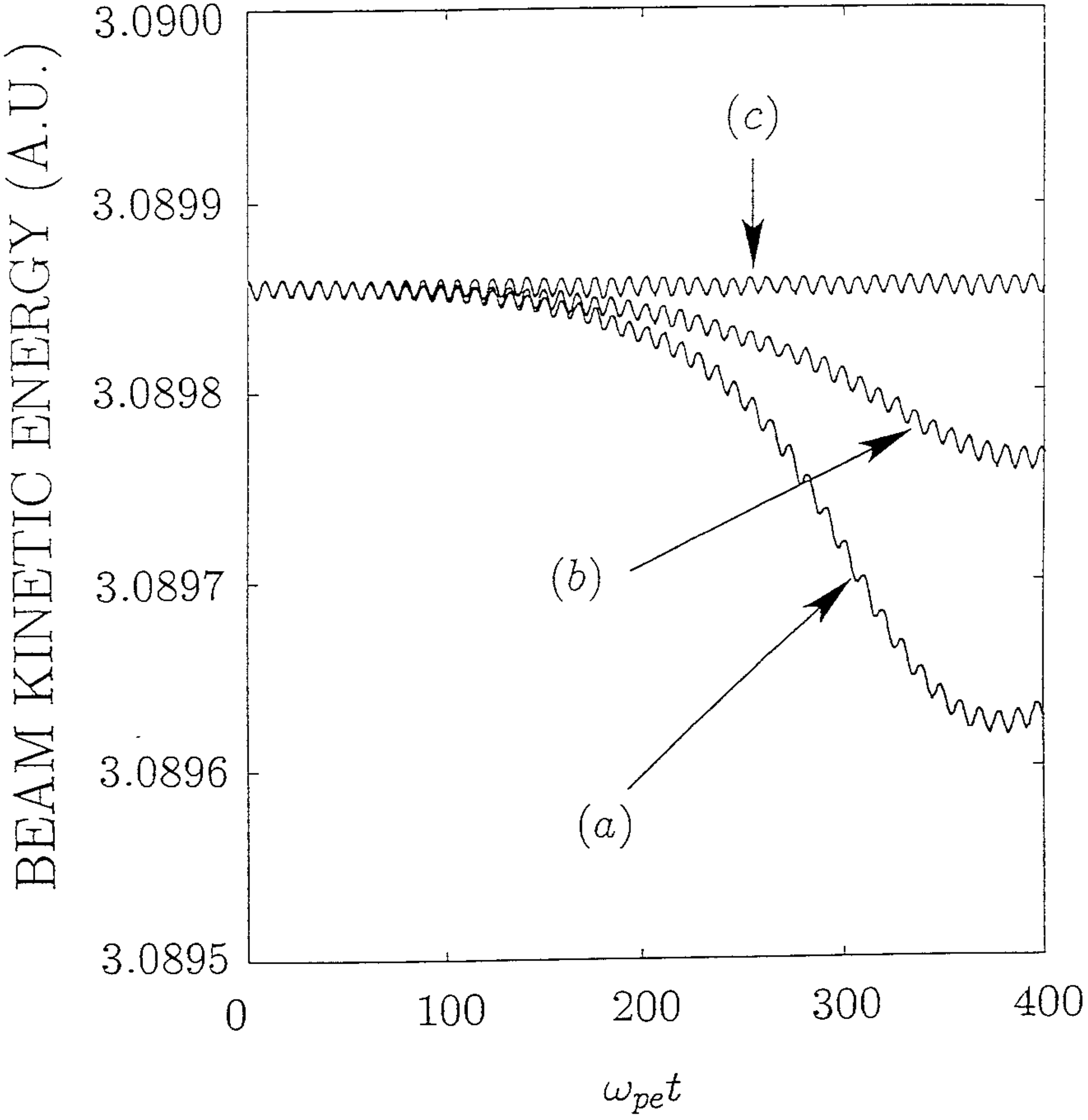

BEAM KINETIC ENERGY (A.U.)
3.0900
3.0899
3.0898
3.0897
3.0896
3.0895
0
100
200
300
400
$\omega_{pe}t$
(a)
(b)
(c)

Fig.3

Recent Issues of NIFS Series

NIFS-298 A. Komori, N. Ohyabu, T. Watanabe, H. Suzuki, A. Sagara, N. Noda, K. Akaishi, N. Inoue, Y. Kubota, O Motojima, M. Fujiwara and A. Iiyoshi, *Local Island Divertor Concept for LHD*; Aug. 1994 (IAEA-CN-60/F-P-4)

NIFS-299 K. Toi, T. Morisaki, S. Sakakibara, A. Ejiri, H. Yamada, S. Morita, K. Tanaka, N. Nakajima, S. Okamura, H. Iguchi, K. Ida, K. Tsumori, S. Ohdachi, K. Nishimura, K. Matsuoka, J. Xu, I. Yamada, T. Minami, K. Narihara, R. Akiyama, A. Ando, H. Arimoto, A. Fujisawa, M. Fujiwara, H. Idei, O. Kaneko, K. Kawahata, A. Komori, S. Kubo, R. Kumazawa, T. Ozaki, A. Sagara, C. Takahashi, Y. Takita and T. Watari, *Impact of Rotational-Transform Profile Control on Plasma Confinement and Stability in CHS*; Aug. 1994 (IAEA-CN-60/A6/C-P-3)

NIFS-300 H. Sugama and W. Horton, *Dynamical Model of Pressure-Gradient-Driven Turbulence and Shear Flow Generation in L-H Transition;* Aug. 1994 (IAEA/CN-60/D-P-I-11)

NIFS-301 Y. Hamada, A. Nishizawa, Y. Kawasumi, K.N. Sato, H. Sakakita, R. Liang, K. Kawahata, A. Ejiri, K. Narihara, K. Sato, T. Seki, K. Toi, K. Itoh, H. Iguchi, A. Fujisawa, K. Adachi, S. Hidekuma, S. Hirokura, K. Ida, M. Kojima, J. Koog, R. Kumazawa, H. Kuramoto, T. Minami, I. Negi, S. Ohdachi, M. Sasao, T. Tsuzuki, J. Xu, I. Yamada, T. Watari, *Study of Turbulence and Plasma Potential in JIPP T-IIU Tokamak*; Aug. 1994 (IAEA/CN-60/A-2-III-5)

NIFS-302 K. Nishimura, R. Kumazawa, T. Mutoh, T. Watari, T. Seki, A. Ando, S. Masuda, F. Shinpo, S. Murakami, S. Okamura, H. Yamada, K. Matsuoka, S. Morita, T. Ozaki, K. Ida, H. Iguchi, I. Yamada, A. Ejiri, H. Idei, S. Muto, K. Tanaka, J. Xu, R. Akiyama, H. Arimoto, M. Isobe, M. Iwase, O. Kaneko, S. Kubo, T. Kawamoto, A. Lazaros, T. Morisaki, S. Sakakibara, Y. Takita, C. Takahashi and K. Tsumori, *ICRF Heating in CHS*; Sep. 1994 (IAEA-CN-60/A-6-I-4)

NIFS-303 S. Okamura, K. Matsuoka, K. Nishimura, K. Tsumori, R. Akiyama, S. Sakakibara, H. Yamada, S. Morita, T. Morisaki, N. Nakajima, K. Tanaka, J. Xu, K. Ida, H. Iguchi, A. Lazaros, T. Ozaki, H. Arimoto, A. Ejiri, M. Fujiwara, H. Idei, A. Iiyoshi, O, Kaneko, K. Kawahata, T. Kawamoto, S. Kubo, T. Kuroda, O. Motojima, V.D. Pustovitov, A. Sagara, C. Takahashi, K. Toi and I. Yamada, *High Beta Experiments in CHS*; Sep. 1994 (IAEA-CN-60/A-2-IV-3)

NIFS-304 K. Ida, H. Idei, H. Sanuki, K. Itoh, J. Xu, S. Hidekuma, K. Kondo, A. Sahara, H. Zushi, S.-I. Itoh, A. Fukuyama, K. Adati, R. Akiyama, S. Bessho, A. Ejiri, A. Fujisawa, M. Fujiwara, Y. Hamada, S. Hirokura, H. Iguchi, O. Kaneko, K. Kawahata, Y. Kawasumi, M. Kojima, S. Kubo, H. Kuramoto, A. Lazaros, R. Liang, K. Matsuoka, T. Minami, T. Mizuuchi, T. Morisaki, S. Morita,

K. Nagasaki, K. Narihara, K. Nishimura, A. Nishizawa, T. Obiki, H. Okada, S. Okamura, T. Ozaki, S. Sakakibara, H. Sakakita, A. Sagara, F. Sano, M. Sasao, K. Sato, K.N. Sato, T. Saeki, S. Sudo, C. Takahashi, K. Tanaka, K. Tsumori, H.Yamada, I. Yamada, Y. Takita, T. Tuzuki, K. Toi and T. Watari, *Control of Radial Electric Field in Torus Plasma;* Sep. 1994 (IAEA-CN-60/A-2-IV-2)

NIFS-305 T. Hayashi, T. Sato, N. Nakajima, K. Ichiguchi, P. Merkel, J. Nührenberg, U. Schwenn, H. Gardner, A. Bhattacharjee and C.C.Hegna, *Behavior of Magnetic Islands in 3D MHD Equilibria of Helical Devices*; Sep. 1994 (IAEA-CN-60/D-2-II-4)

NIFS-306 S. Murakami, M. Okamoto, N. Nakajima, K.Y. Watanabe, T. Watari, T. Mutoh, R. Kumazawa and T. Seki, *Monte Carlo Simulation for ICRF Heating in Heliotron/Torsatrons*; Sep. 1994 (IAEA-CN-60/D-P-I-14)

NIFS-307 Y. Takeiri, A. Ando, O. Kaneko, Y. Oka, K. Tsumori, R. Akiyama, E. Asano, T. Kawamoto, T. Kuroda, M. Tanaka and H. Kawakami, *Development of an Intense Negative Hydrogen Ion Source with a Wide-Range of External Magnetic Filter Field*; Sep. 1994

NIFS-308 T. Hayashi, T. Sato, H.J. Gardner and J.D. Meiss, *Evolution of Magnetic Islands in a Heliac*; Sep. 1994

NIFS-309 H. Amo, T. Sato and A. Kageyama, *Intermittent Energy Bursts and Recurrent Topological Change of a Twisting Magnetic Flux Tube*; Sep.1994

NIFS-310 T. Yamagishi and H. Sanuki, *Effect of Anomalous Plasma Transport on Radial Electric Field in Torsatron/Heliotron*; Sep. 1994

NIFS-311 K. Watanabe, T. Sato and Y. Nakayama, *Current-profile Flattening and Hot Core Shift due to the Nonlinear Development of Resistive Kink Mode*; Oct. 1994

NIFS-312 M. Salimullah, B. Dasgupta, K. Watanabe and T. Sato, *Modification and Damping of Alfvén Waves in a Magnetized Dusty Plasma*; Oct. 1994

NIFS-313 K. Ida, Y. Miura, S -I. Itoh, J.V. Hofmann, A. Fukuyama, S. Hidekuma, H. Sanuki, H. Idei, H. Yamada, H. Iguchi, K. Itoh, *Physical Mechanism Determining the Radial Electric Field and its Radial Structure in a Toroidal Plasma*; Oct. 1994

NIFS-314 Shao-ping Zhu, R. Horiuchi, T. Sato and The Complexity Simulation Group, *Non-Taylor Magnetohydrodynamic Self-Organization*; Oct. 1994

NIFS-315 M. Tanaka,
Collisionless Magnetic Reconnection Associated with Coalescence of Flux Bundles; Nov. 1994

NIFS-316 M. Tanaka,
Macro-EM Particle Simulation Method and A Study of Collisionless Magnetic Reconnection; Nov. 1994

NIFS-317 A. Fujisawa, H. Iguchi, M. Sasao and Y. Hamada,
Second Order Focusing Property of 210° Cylindrical Energy Analyzer; Nov. 1994

NIFS-318 T. Sato and Complexity Simulation Group,
Complexity in Plasma - A Grand View of Self- Organization; Nov. 1994

NIFS-319 Y. Todo, T. Sato, K. Watanabe, T.H. Watanabe and R. Horiuchi,
MHD-Vlasov Simulation of the Toroidal Alfvén Eigenmode; Nov. 1994

NIFS-320 A. Kageyama, T. Sato and The Complexity Simulation Group,
Computer Simulation of a Magnetohydrodynamic Dynamo II: Nov. 1994

NIFS-321 A. Bhattacharjee, T. Hayashi, C.C.Hegna, N. Nakajima and T. Sato,
Theory of Pressure-induced Islands and Self-healing in Three-dimensional Toroidal Magnetohydrodynamic Equilibria; Nov. 1994

NIFS-322 A. Iiyoshi, K. Yamazaki and the LHD Group,
Recent Studies of the Large Helical Device; Nov. 1994

NIFS-323 A. Iiyoshi and K. Yamazaki,
The Next Large Helical Devices; Nov. 1994

NIFS-324 V.D. Pustovitov
Quasisymmetry Equations for Conventional Stellarators; Nov. 1994

NIFS-325 A. Taniike, M. Sasao, Y. Hamada, J. Fujita, M. Wada,
The Energy Broadening Resulting from Electron Stripping Process of a Low Energy Au^- *Beam;* Dec. 1994

NIFS-326 I. Viniar and S. Sudo,
New Pellet Production and Acceleration Technologies for High Speed Pellet Injection System "HIPEL" in Large Helical Device; Dec. 1994

NIFS-327 Y. Hamada, A. Nishizawa, Y. Kawasumi, K. Kawahata, K. Itoh, A. Ejiri, K. Toi, K. Narihara, K. Sato, T. Seki, H. Iguchi, A. Fujisawa, K. Adachi, S. Hidekuma, S. Hirokura, K. Ida, M. Kojima, J. Koong, R. Kumazawa, H. Kuramoto, R. Liang, T. Minami, H. Sakakita, M. Sasao, K.N. Sato, T. Tsuzuki, J. Xu, I. Yamada, T. Watari,
Fast Potential Change in Sawteeth in JIPP T-IIU Tokamak Plasmas;

Dec. 1994

NIFS-328 V.D. Pustovitov,
Effect of Satellite Helical Harmonics on the Stellarator Configuration; Dec. 1994

NIFS-329 K. Itoh, S-I. Itoh and A. Fukuyama,
A Model of Sawtooth Based on the Transport Catastrophe; Dec. 1994

NIFS-330 K. Nagasaki, A. Ejiri,
Launching Conditions for Electron Cyclotron Heating in a Sheared Magnetic Field; Jan. 1995

NIFS-331 T.H. Watanabe, Y. Todo, R. Horiuchi, K. Watanabe, T. Sato,
An Advanced Electrostatic Particle Simulation Algorithm for Implicit Time Integration; Jan. 1995

NIFS-332 N. Bekki and T. Karakisawa,
Bifurcations from Periodic Solution in a Simplified Model of Two-dimensional Magnetoconvection; Jan. 1995

NIFS-333 K. Itoh, S.-I. Itoh, M. Yagi, A. Fukuyama,
Theory of Anomalous Transport in Reverse Field Pinch; Jan. 1995

NIFS-334 K. Nagasaki, A. Isayama and A. Ejiri
Application of Grating Polarizer to 106.4GHz ECH System on Heliotron-E; Jan. 1995

NIFS-335 H. Takamaru, T. Sato, R. Horiuchi, K. Watanabe and Complexity Simulation Group,
A Self-Consistent Open Boundary Model for Particle Simulation in Plasmas; Feb. 1995

NIFS-336 B.B. Kadomtsev,
Quantum Telegragh : is it possible?; Feb. 1995

NIFS-337 B.B.Kadomtsev,
Ball Lightning as Self-Organization Phenomenon; Feb. 1995

NIFS-338 Y. Takeiri, A. Ando, O. Kaneko, Y. Oka, K. Tsumori, R. Akiyama, E. Asano, T. Kawamoto, M. Tanaka and T. Kuroda,
High-Energy Acceleration of an Intense Negative Ion Beam; Feb. 1995

NIFS-339 K. Toi, T. Morisaki, S. Sakakibara, S. Ohdachi, T.Minami, S. Morita, H. Yamada, K. Tanaka, K. Ida, S. Okamura, A. Ejiri, H. Iguchi, K. Nishimura, K. Matsuoka, A. Ando, J. Xu, I. Yamada, K. Narihara, R. Akiyama, H. Idei, S. Kubo, T. Ozaki, C. Takahashi, K. Tsumori,
H-Mode Study in CHS; Feb. 1995