Activity at Hiroshima University

The Beam Physics Group (BPG) at Hiroshima University was organized in October 1998, as a new group belonging to the Graduate School of Advanced Sciences of Matter (AdSM). Since then, efforts have been made to initiate various theoretical and experimental research programs of beam physics.

BPG is also playing an important role in the Japanese beam-physics community [1].

1. Space-Charge-Dominated Beam Physics

Solving the Vlasov-Poisson equations for a one-dimensional beam, we found the coherent resonance condition [2,3]

$$\Omega_m \equiv m(\nu_0 - C_m \Delta\nu) = \frac{n}{2}, \tag{1}$$

where Ω_m is the tune of the mth–order coherent mode, ν_0 is the bare tune, $\Delta\nu = \nu_0 - \nu_x$ with ν_x being the depressed single-particle tune, and C_m's are certain constants. Resonance calculations for circulating two-dimensional beams have also been done numerically. The betatron Hamiltonian, including the effect of momentum dispersion, is given by

$$\begin{aligned}\tilde{H} = {} & \frac{\tilde{p}_x^2 + \tilde{p}_y^2}{2} + \frac{1}{2}(K_x - K_{sc}\xi_{20})\tilde{x}^2 + \frac{1}{2}(K_y - K_{sc}\xi_{02})\tilde{y}^2 \\ & - \frac{K_{sc}\xi_{40}}{24}\left[\tilde{x}^4 + 4D_x^{(1)}W\tilde{x}^3 + 6(D_x^{(1)})^2 W^2 \tilde{x}^2\right] - \frac{K_{sc}\xi_{04}}{24}\tilde{y}^4 - \frac{K_{sc}\xi_{22}}{4}\left[\tilde{x}^2 + 2D_x^{(1)}W\tilde{x} + (D_x^{(1)})^2 W^2\right]\tilde{y}^2 + \cdots,\end{aligned} \tag{2}$$

where we have assumed the same notation as used in Ref. [4]. Equation (2) strongly suggests the existence of *dispersive resonances*. We have actually confirmed, through particle-in-cell simulations, that such a novel resonance mechanism does affect the beam quality.

In order to improve the quality of a beam, we often introduce some cooling device in a storage ring. Since the tune is gradually depressed as the beam temperature becomes lower, the operating point may cross resonance stopbands. It is thus important to figure out whether a resonance can interrupt the cooling process. Systematic numerical simulations showed that the effective tune is locked at a low-order stopband if the cooling force is weak [5].

For the study of diverse space-charge effects, we proposed a new experimental scheme utilizing non-neutral plasma traps [6,7]. Two types of trap configurations, i.e. a radio-frequency quadrupole trap (Paul trap) and a solenoidal trap, were considered. The reason why these trap systems can be used for the study of charged-particle beams in accelerators is quite simple; a beam seen from the rest frame is almost equivalent to a single-species plasma in a trap. In fact, charged particles in a long Paul trap obey the Hamiltonian

$$H_{trap} = \frac{p_x^2 + p_y^2}{2} + \frac{1}{2}K(\tau)(x^2 - y^2) + \frac{q}{m_0 c^2}\phi(x, y; \tau), \tag{3}$$

where q and m_0 are, respectively, the charge state and rest mass of the particles, the independent variable is $\tau = ct$ with c being the speed of light, and $K(\tau)$ is a periodic function proportional to the radio-frequency voltages applied to the electrodes. Clearly, Eq. (3) has the form identical to the well-known Hamiltonian of betatron motion in a linear transport system, which means that the trap system can reproduce collective phenomena equivalent to those in a beam transport channel.

2. Phase Transition of Ion Beams

At low-temperature limit, a single-species plasma reaches a unique ordered state known as a *Coulomb crystal*. Recalling the dynamical analogy between a trap and a beam transport channel as discussed in the last section, we expect that a similar state may be established even in a cooler storage ring. Molecular dynamic simulations have actually shown that it is possible to crystallize a fast stored beam, at least, in principle. At BPG, the nature of this *crystalline beam* has been extensively studied. In a crystalline ground state, the trajectories of individual particles are strongly correlated; the transverse spatial coordinates of each particle in a coasting crystalline beam can be expressed as $x = C_x D_x(s), \quad y = C_y D_y(s),$ where D_x and D_y are periodic functions of the path length s while C_x and C_y depend on which particle we see [8]. The orbit functions D_x and D_y satisfy coupled differential equations analogous to the envelope equations. It is an easy matter to show that the emittance of a crystalline beam is exactly zero. Provided that a longitudinal radio-frequency field is present, the motion of a crystalline beam becomes more complex due to the existence of momentum dispersion [9].

To our best knowledge, laser cooling is currently the only means for us to reach a crystalline state, considering the acceptable thermal noise level. However, the dissipative force generated by a laser light has been known to operate only in the longitudinal direction of beam motion. In order to extend the powerful laser-cooling force to the transverse degrees of freedom, we have been testing the *resonant coupling method* [10,11]. It has been verified that the coupling scheme can significantly improve the transverse cooling efficiency [12].

The dispersive effect peculiar to a storage ring imposes a special demand upon the nature of cooling force for stabilizing crystals. Since the revolution frequencies of all particles forming a crystalline beam are identical, a longitudinal laser must provide such a cooling force as to give a greater average velocity to a radially outer particle. This is often referred to as *tapered cooling* [13]. If too powerful a conventional laser is applied, multi-dimensional crystalline structure could be destroyed because the *untapered* friction simply equalizes the longitudinal velocities of all particles. To develop a practical method for generating a tapered light seems to be the most important future issue toward our final goal.

3. Study of Compact Accelerators

It is over fifteen years ago that the idea of using solid structures for particle acceleration was discussed by several researchers. Nevertheless, no proof-of-principle experiments have been performed yet. One primary reason is that the power source appropriate for this purpose is not available. Recently, we have considered the application of artificial macroscopic structures, instead of natural solids, such as a photonic band-gap crystal. The characteristic size of an accelerator structure can then be enlarged to the order of 1μm, much greater than the typical lattice constant of a solid [14].

An alternative, even simpler possibility is the use of a tiny cylindrical hole in a solid. By injecting a laser light into the hole, we can excite *plasmons* along the inner surface if the aperture size is comparable to the laser wavelength. The potential of the plasmons can be utilized to accelerate charged particles [15]. The conversion efficiency of the laser power to the accelerating field is expected to be rather high; e.g., a MW laser should suffice for attaining a gradient of GeV/m level. This scheme is, in some sense, similar to laser wake-field acceleration in a hollow channel and also to a dielectric linac. However, the *plasmon linac* could supply a beam of nanometer in transverse size (though the attainable beam current would be low). Figure 1 shows the dispersion diagram of a typical plasmon linac whose aperture radius is a. ω_p is the plasma frequency and the corresponding wave number has been denoted by $k_p = \omega_p / c$. The frequencies of all modes approach the surface plasmon-polariton frequency $\omega_p / \sqrt{2}$ as the wave number k increases. The two straight lines in the picture represent the dispersion of the accelerating waves whose phase velocities are $v_p = c$ and $c / 2$. To accelerate an electron beam traveling nearly at the speed of light, we simply use a laser that has the frequency at the intersection between the plasmon dispersion curve and the $v_p = c$ line.

Suppose a plasmon linac made of silver. When $k_p a = 10$ and $v_p = c$, the required aperture radius and laser wavelength are, respectively, 227 nm and 344 nm. In this case, an acceleration gradient of 45.0 GeV/m is achievable with a 1MW laser according to our estimate. The effective acceleration length is, however, only about 4.3 μm, which means that the total energy gain is less than 200 keV. This is basically due to the ohmic loss that raises the temperature of the linac and may eventually destroy the whole structure. One possible way to minimize this heating effect is to operate the linac in an extremely low-temperature atmosphere. At 10 K, for instance, the resistivity of silver becomes 1400 times smaller than that at room temperature. Consequently, the acceleration length and energy gain are increased to 6.1 mm and 273 MeV, respectively. Further, the

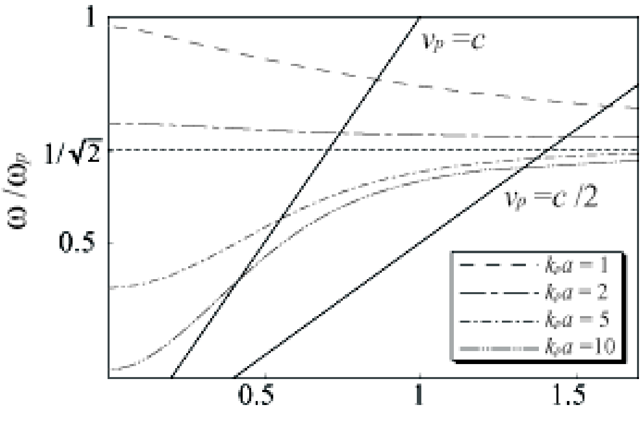

Fig. 1 : Dispersion diagram of plasmons.

power loss at $r = a$ could be kept below the damage threshold of silver unless the repetition rate is too high.

4. Laser-Matter Interactions

For the last several years, there has been growing interest in interactions between high-intensity lasers and matters. In particular, the generation of multi-MeV ions by the irradiation of a high-power (> 10 TW), short-pulse (< 1 ps) laser has attracted worldwide attention. If an analogous effect is realizable by a laser of much lower power, that gives us a possibility of developing a compact ion source for diverse purposes.

The BPG has been performing experiments to irradiate very thin plastic and metal foils by a relatively low-power laser (1 TW) having a pulse width (50 fs) shorter than hitherto experiments [16]. The wavelength and pulse frequency of our laser are 800 nm and 10 Hz. Because the system is not equipped with a pulse cleaner, a main pulse is accompanied by a prepulse with amplitude 1/1000 - 1/100 of the main. It was, however, suggested that the existence of prepulses causes some positive effect in high-energy ion generation [18]. Two types of materials (mylar and aluminum) whose thickness are mostly less than 10 μm have so far been used as a target. It was found that the intensity threshold of ion generation is $10^{17}\ \mathrm{W \cdot cm^{-2}}$ in the "forward" region (In what follows, we call the laser-illuminated side "backward" and the other side "forward"; particles produced below this threshold had no charge. By contrast, no such threshold was observed as to the particle generation toward the backward direction. The most energetic particles were usually protons in both directions, and the highest energy detected at the laser power of $2 \times 10^{17}\ \mathrm{W \cdot cm^{-2}}$ was about 800 keV. Figure 2 shows a photograph at the moment of the interaction. The visible radiation was spectroscopically analyzed [17].

Energetic neutral particle beams were also observed in addition to ions[16]. They are produced mainly in the forward direction, and the divergence angle is much less than that of ions. According to our spectroscopic data, hydrogen atoms are the most probable candidate; if we assume so, systematic measurements with CR39 track detectors suggest that the maximum energy is beyond 1 MeV. The mechanism of neutral-beam generation has not been understood yet.

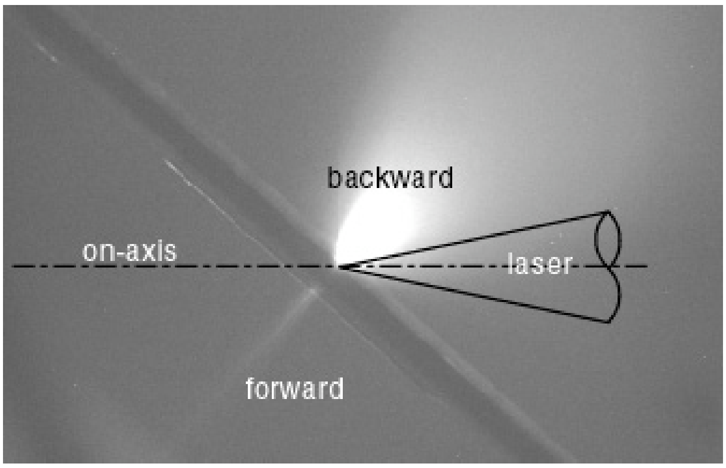

Fig. 2 : Photograph taken at the moment of laser irradiation to an Al foil of 3 μm in thickness. A laser is coming from the right side. The target foil is tilted by 45 degrees with respect to the laser axis.

References

1. The homepage of the Japanese Beam Physics Club can be found at http://www-acc-theory.kek.jp/BP/BPclub.html (only in Japanese); See also:

H. Okamoto, The Japanese beam physics club and its recent activities, *ICFA Beam Dynamics Newsletter* No.12 (1996) p.10.

2. H. Okamoto and K. Yokoya, "Parametric resonances in intense one-dimensional beams propagating through a periodic focusing channel", Nucl. Instr. Meth. A482 (2002) p.51.
3. A. V. Fedotov, I. Hofmann, R. L. Gluckstern and H. Okamoto, "Parametric collective resonances and space-charge limit inhigh-intensity rings", Phys. Rev. STAB 6 (2003) 094201.
4. H. Okamoto and S. Machida, "Particle beam resonances driven by dispersion and space charge", Nucl. Instr. Meth. A482 (2002) p.65.
5. K. Okabe and H. Okamoto, "Emittance limitation in cooled hadron beams", Hiroshima University Preprint HUBP-02/02 (2002), Jpn. J. Appl. Phys. 42 (2003) 4584.
6. H. Okamoto, "On dynamical analogy between linear beam transport channels and plasma trap systems", Hiroshima University Preprint HUBP-01/98 (1998); H. Okamoto and H. Tanaka, "Proposed experiments for the study of beam halo formation", Nucl. Instr. Meth. A 437 (1999) p.178.
7. H. Okamoto, Y. Wada and R. Takai, "Radio-frequency quadrupole trap as a tool for experimental beam physics", Nucl. Instr. Meth. A 485 (2002) p.244.
8. H. Okamoto, "Single-particle orbit equation in crystalline beams", Phys. Plasmas 9 (2002) p.322.
9. H. Okamoto, Y. Yuri and K. Okabe, "Oscillating Coulob chain in a storage ring", Phys. Rev. E 67 (2003) 046501; Y. Yuri and H. Okamoto, "Effect of a longitudinal radio-frequency field on crystalline beams", J. Phys. Soc. Jpn. 71 (2002) p.1003
10. H. Okamoto, A. M. Sessler and D. Möhl, "Three-dimensional laser cooling of stored and circulating ion beams by means of a coupling cavity", Phys. Rev. Lett. 72 (1994) p.3977; H. Okamoto, "Transverse laser cooling induced through dispersion at an rf cavity", Phys. Rev. E 50 (1994) p.4982.
11. H. Okamoto, Y. Yuri and K. Okabe, "Some remarks on beam crystallization", *Ion Beam Cooling – Toward the Beam Crystallization*, World Scientific Publishing Co., Singapore (2002) p.160.
12. T. Kihara et. al., "Three-dimensional laser cooling method based on resonant linear coupling", Phys. Rev. E 59 (1999) p.3594.
13. J. Wei, H. Okamoto and A. M. Sessler, "Necessary conditions for attaining a crystalline beam", Phys. Rev. Lett. 80 (1998) p.2606; H. Okamoto and J. Wei, "Theory of tapered cooling", Phys. Rev. E 58 (1998) p.3817.
14. A. Ogata, "Use of macroscopic solid structure in accelerators", to be published in Proc. 3rd QABP Workshop.
15. N. Saito and A. Ogata, "Plasmon linac: A laser wake-field accelerator based on a solid-state plasma", Phys. Plasmas, 10 (2003) p.3358.
16. Y. Wada, T. Kubota and A. Ogata, "Neutral beam generation by laser irradiation of thin foils", in K. Nakajima and M. Deguchi (eds), Sciences of Superstrong Field Interactions, no.634 in AIP Conf. Proc. (2002) p.329.
17. T. Kubota, Y. Wada, and A. Ogata, "Visible Spectroscopy in T3 Laser Interaction with Thin Foil Targets", Jpn. J. Appl. Phys. 42 (2003) in press.
18. K. Matsukado, T. Esirkepov, K. Kinoshita, H. Daido, T. Utsumi, Z. Li, A. Fukumi, Y. Hayashi, S. Orimo, M. Nishiuchi, S. V. Bulanov, T. Tajima, A. Noda, Y. Iwashita, T. Shirai, T. Takeuchi, S. Nakamura, A. Yamazaki, M. Ikegami, T. Mihara, A. Morita, M. Uesaka, K. Yoshii, T. Watanabe, T. Hosokai, A. Zhidkov, A. Ogata, Y. Wada, and T. Kubota, "Energetic Protons from a Few Micron Metallic Foil Evaporated by Intense Laser Pulse", Phys. Rev. Lett. 91 (2003) 215001.