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A Novel High-Energy Ion-Beam Driver and its Applications

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A novel medium-energy synchrotron capable of accelerating all ion species is proposed as an ion driver for exploring new paradigms in material science. All ions, including cluster ions in their possible and arbitrary charge state, are accelerated in an injector-free single accelerator. The principle of accelerator is based on that of the induction synchrotron, which has been recently demonstrated at KEK. Various high-energy ions provided from the ion driver will be used in a way of penetration through bulk materials leaving large substantial electro-excitation energy. Uniform or localized implantation of energetic ions into the materials are rather general but still attractive approaches to create novel materials, such as a shock absorbing alloy with a soft layer underneath hard surface.

Keywards: synchrotron, all-ion accelerator, induction, warm dense matter, bulk material

1. INTRODUCTION

For more than 70 years since its invention in the 1930's [1], the cyclotron has evolved in its various forms, and has been become quite familiar for the acceleration of most ion species to a medium energy range of multi-hundreds of MeV/au. Any ions that have the same Z/A, where A is the mass number and Z is the charge state, can in principle be accelerated by the same cyclotron. For the acceleration of particular ions far beyond the medium energy region, rf synchrotrons have been used. The SIS-18 synchrotron of GSI is a typical one [2] and devoted to material science [3] or warm dense matter science [4], providing H, D, C, N, O, Ne, Ar, Ni, Kr, Xe, Au, Bi, and U. The accelerators mentioned above are classified as resonant accelerators employing radio-frequency waves for acceleration. Electric fields varying in time give the required energy per turn and provide the focusing forces in the moving direction.

Once the synchrotron is determined to operate on protons, an rf acceleration system consisting of an rf cavity and an rf power-source is fixed. In a typical medium-energy synchrotron, the rf frequency sweeps by one order of magnitude through its entire acceleration associated with increasing the revolution frequency, where the relativistic beta changes from 0.1 to some value close to unity. The kinetic energy of an ion is described by $Amc^2(\gamma-1)$, where γ is the relativistic gamma of the ion, and m is the proton mass; in the non-relativistic region it is approximated by $(1/2)Amc^2\beta^2$, where β is the relativistic beta. This formula suggests that the injection energy must be above $4.69A$ MeV to meet the rf frequency minimum limit. In other words, the integrated acceleration voltage in an upstream injector must be $V=4.69(A/Z)$ MeV. So far, this required voltage has been provided by a gigantic static accelerator, such as a Van de Graff, or by a drift-tube linac. An electro-static accelerator of larger energy than tens of MeV is not practical because of a technical limit of high-voltage breakdown and its huge cost. It is noted that the A/Z of an ion accepted in the drift-tune linac, which is usually an injector for the synchrotron, is limited by its rf frequency. The limit on A/Z is a principal limit for rf accelerators.

Recently, a novel concept of injector-free synchrotron, which allows the acceleration of all species of ions in a single ring, has been proposed [5]. In order to overcome the principal limit, a newly developed acceleration technology of induction acceleration is employed to realize the concept. Such a synchrotron is called an all-ion accelerator (AIA); its characteristics and key issues are reviewed below.

So far, the irradiation of various ions on metal, magnetic material, ceramic, semi-conducting material, and polymer has been discussed to develop novel materials, such as nano-wire, nano-transistors, quantum-dots, and conducting ion tracks in diamond-like carbon [3]. Deep implant of moderate-energy heavy ions may serve to create a new alloy in bulk size. Meanwhile, energy deposition caused by the electro-excitation associated with passing of high-energy ions through the material is known to largely modify its structure [6]. Warm dense matter science is going to drastically evolve with the aid of high-power laser and heavy-ion beams [4,7]. The irradiation of moderate-energy heavy-ion beams on metal in a small physical space of less than a mm in diameter and in a short time period less than 100 nsec is known to create a particularly interesting state of material, where the temperature is 0.1-10 eV and the mass density is 1 g/cm^3. This state of matter is far from playing-grounds of solid-state physics and plasma science, where the equation of state has not yet been established, electric conductivity is not known, and the effects of the interactions between atoms are not confirmed. An AIA capable of delivering various heavy ions should be a quite interesting device as a driver to explore these new paradigms.

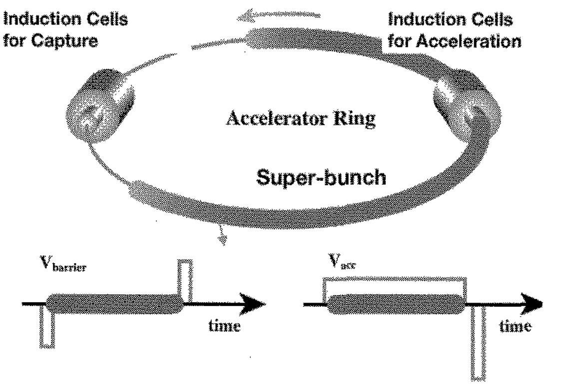

Fig.1.Schematic view of the induction synchrotron. $V_{barrier}$ is the barrier voltage for confinement and V_{acc} is the acceleration voltage for acceleration.

2. FROM INDUCTION SYNCHROTRON TO ALL-ION ACCELERATOR

Recently, the concept of an induction synchrotron [8] has been successfully demonstrated by using the KEK 12 GeV proton synchrotron (KEK-PS) [9], where induction-acceleration devices instead of rf cavities in a conventional synchrotron are employed. In the *induction synchrotron*, the acceleration and longitudinal confinement of charged particles are independently achieved with induction step-voltages. A long step-voltage generated in the induction acceleration cell gives acceleration energy, and a pair of pulse voltages, which are generated at both edges of some time-period with opposite sign, are capable of providing longitudinal focusing forces, as shown in Fig. 1. In an experiment of the *induction synchrotron*, a single proton bunch was trapped in a barrier bucket created with the barrier voltages after injection from the 500 MeV Booster ring, and it was accelerated up to 6 GeV in 2 seconds. The experimental setup is shown in Fig. 2.

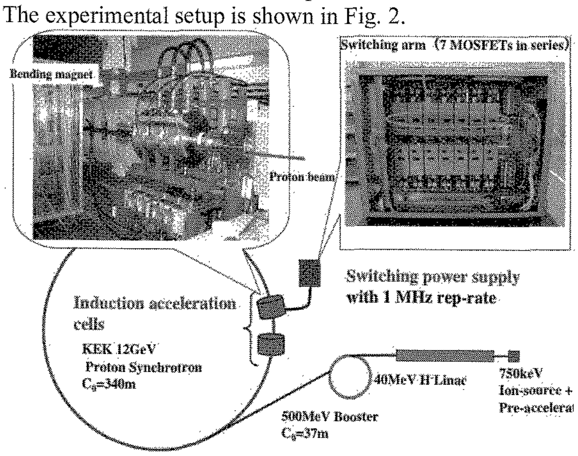

Fig.2. Experimental setup in the KEK 12GeV PS. Top left: induction acceleration cells (output voltage 2kV/cell); Top right: switching power supply; Bottom: the KEK 12 GeV accelerator complex.

The key devices required to realize an *induction synchrotron* are an induction accelerating cell and a switching power-supply [10] to drive the cell. The latter is a kind of pulse modulator, which is capable of generating bipolar rectangular shaped voltage pulses. The full-bridge type switching power-supply consists of four identical switching arms. Each switching arm is composed of solid-state power devices, such as MOS-FETs arranged in series and parallel. Their gates are driven in their own gate-driving circuits. The gate signals are generated by converting light signals provided from the pulse controller, which is a part of the accelerator control system, to electronic signals. It is an essential point in the AIA that these gate signals are definitely able to trigger the required accelerating and confining voltages at the desired timing. If a master signal for these gate signals is generated from a circulating ion-bunch signal, induction pulse-voltages for acceleration and confinement should be automatically synchronized with the revolution of the bunch. This fact suggests that the allowable revolution frequency is not limited if a sufficiently fast switching device is available. This is a big difference from a conventional rf synchrotron or cyclotron, where the range of the acceleration energy or ion mass is limited, since equipped rf devices usually have a finite bandwidth, as mentioned earlier. An accelerator to accelerate all species of ions of their possible charge state from the lightest to the heaviest, the AIA, can be realized when acceleration devices driven by the switching power supply are employed.

In this article, the essential characteristics of the AIA, a schematic view of which is depicted in Fig. 3. are discussed, and its typical composition and numerical parameters are given, assuming that the KEK 500 MeV Booster Synchrotron of a rapid-cycle proton synchrotron, the machine parameters of which are listed in Table, is modified to be an AIA.

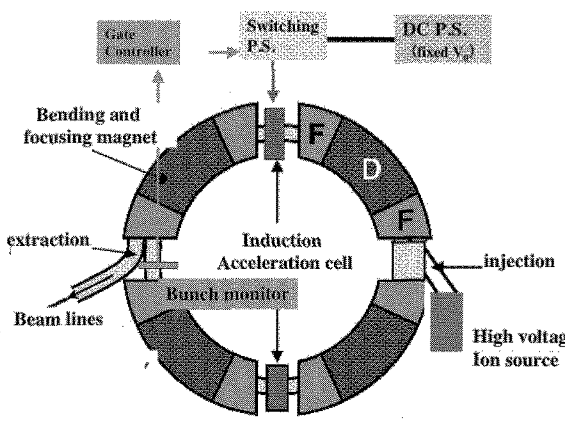

Fig. 3. Schematic view of the all-ion accelerator. The ion-bunch signals monitored by the bunch monitor are processed in the gate controller and gate signal for the switching power supply is generated.

Table Machine Parameters of the KEK-AIA

circumference (m)	C_0	37
curvature (m)	ρ	3.3
minimum field (T) for Ar^{+18}	B_{min}	0.029
maximum field (T) for Ar^{+18}	B_{max}	0.8583
acceleration voltage (kV)	V_{acc}	6.36
operation cycle (Hz)	f	20

3. TYPICAL ACCELERATION EXAMPLE IN THE

AIA

Let think acceleration of Ar ions. Guiding magnets of the AIA are sinously excited by a resonant circuit power supply at a repetition rate of 20 Hz. An increase in the kinetic energy and a temporal change in the revolution frequency and required acceleration voltage for a full stripped Ar ion are given in Fig. 4. The maximum beam current accelerated in the AIA is usually determined by the transverse space-charge limit at injection. We estimtae an Ar beam of 4.7×10^{10} per bunch and 9.4×10^{11} per second. Details of the acceleration scheme are given in the literature [5].

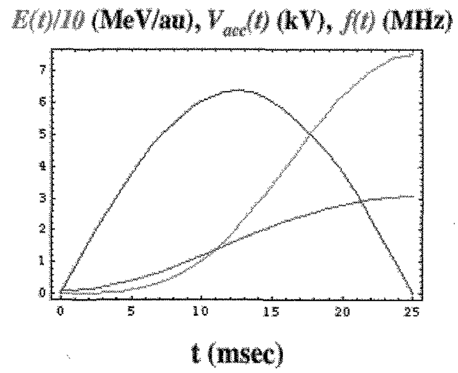

Fig. 4. Changes in energy, acceleration voltage, and revolution frequency vs. time.

4. APPLICATIONS TO MATERIAL SCIENCE

4.1 Warm dense matter science

Heavy-ion beams delivered from the AIA are available for warm dense matter science. It is essential to realize a high-density state with high temperature in a metal target, a parameter region of which is depicted in Fig. 5, how the kinetic energy of a projectile ion-beam is deposited in a limited physical space. We will try to compress the ion beam in the transverse direction by employing a mini-beta optics, which is popular in any colliders for high-energy physics. Meanwhile, the ion bunch will be compressed by a mean of bunch rotation in the longitudinal phase-space, which is carried out by using high gradient RFs or a linear induction accelerator. Utilizing this compression scheme as depicted in Fig. 6, a high-density of 1 g/cm^3 and high-temperature of 0.1-10 eV will be achieved in the physical space of 1 mm in radius and 10 mm in length.

Scientific motivation and significance to explore such a warm dense matter have been addressed in several literatures [4,7].

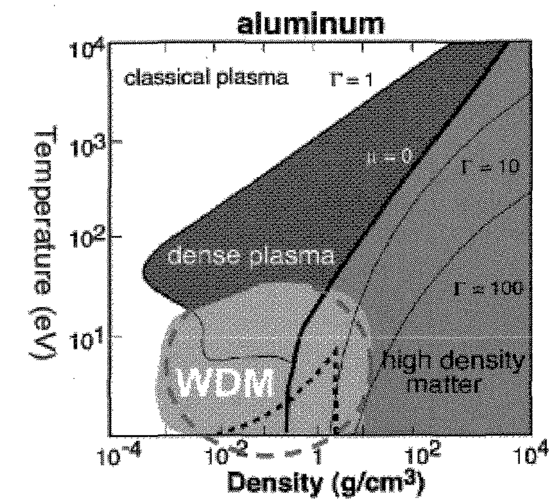

Fig. 5. Parameter region for the WDM science. Γ is a plasma coupling parameter, $\sim n^{1/3}/T$ (n: density, T: temperature). Red broken circle corresponds the parameter region of WDM.

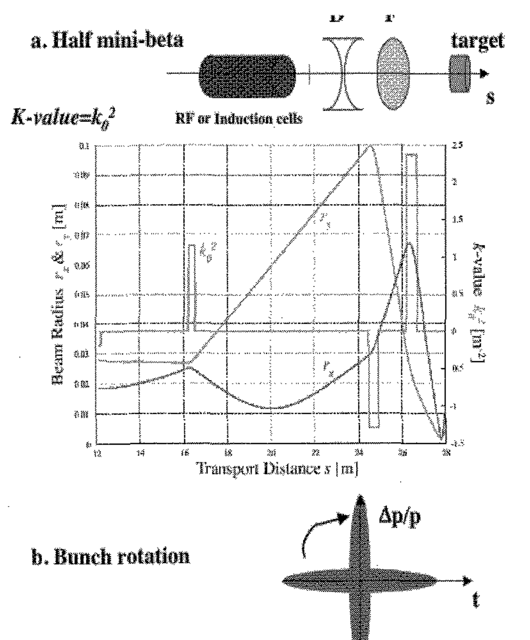

Fig. 6. Beam compression scheme. Top: beam sizes in the transverse direction, fucusing/defocusing parameters for the mini-beta system consisting of a pair of focusing and defocusing magnet (the right edge is the target position); Bottom: schematic phase-plot in the longitudinal phase space (t, $\Delta p/p$).

4.2 Bulk material science

So far the use of high-energy ion-beams in material science may have been limited to studies, such as lattice defect induced by impinging ions. It is true that many attractive applications of swift ions have been demonstrated mainly in Europe for the last decade, by employing heavy ion beams delivered from the GANIL cyclotron or the SNS-18 of GSI. The ion beam specification of the latter synchrotron is rather close to that of he present novel synchrotron, although ion species and their charge states are limited. A high-energy ion beam has a long range in target materials, depending on its energy, mass number, charge-state, and target material. For an example of Ar^{+18} of 75 MeV/au in metal targets, the range in order of a few cm is estimated. This fact allows implant of desired ions into such a bulk metal, by combining a kind of energy dumper of a tapered ribbon metal, which rotates to sweep the Bragg peak in the bulk target material. (See Fig. 7)

On the other hand, a high-energy ion only deposits a substantial fraction of its kinetic energy, exciting encountering atoms by the Coulomb interaction if the kinetic energy is sufficiently enough to penetrate through the target material.

Uniform irradiation on a bulk material is crucial. A specific beam expanding system, such as a wobbler magnet or nonlinear defocusing magnets, will be employed, which uniformly expands a projectile ion beam of cm in diameter to 10 cm size.

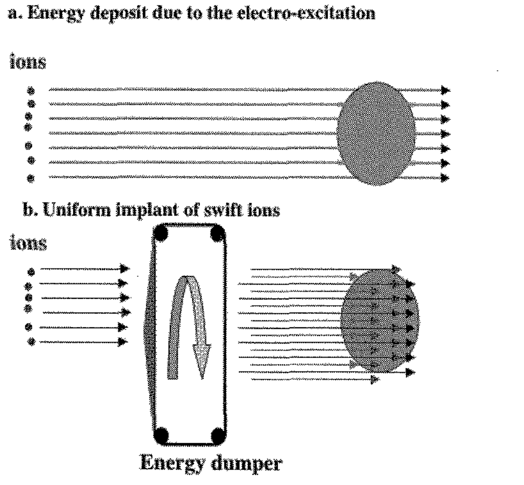

Fig. 7. Essential interaction between high-energy ions and bulk materials

5. HEAVY-ION BEAM FACILITY

Heavy ion beams extracted from the AIA will be delivered into two beam lines of (1) the WDM beam line and (2) the material science beam line. In the former experiment, the real time measurement of temperature, density, and conductivity is indispensable; the diagnosis system, such as a streak camera and polychrometor, is going to be installed. Real-time data will be transferred through optical fiber cables to the central control room. The target station should be placed just in front of the beam dump.

In most of the latter experiment, high irradiation dose is required and consequently obtained results are of interest. During the irradiation, the deposited heat is significant and must be extracted by any appropriate heat exchanging system. After a bulk sample is irradiated, it should be temporally at a high level of residual radiation. The sample must be cooled down in a secured space for succeeding various diagnosis for a while; then, it will be released for the diagnosis.

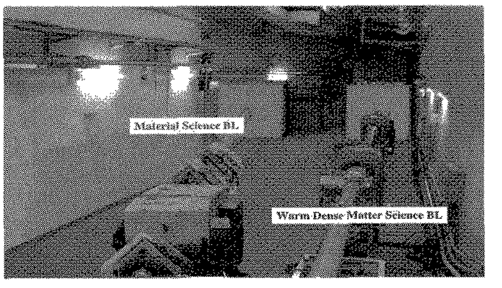

Fig. 8. Typical view of the beam lines (image). Right: the beam line for warm dense matter science and Left: the beam line for material science. Far ends of the beam lines: irradiation stands and beam dumps

6. SUMMARY

It is noted that we have not discussed details about warm dense matter science and material science, which can be developed in this plan. They will be extensively described in forthcoming papers. Novel aspects of experimental tools to realize these scientific targets have been presented here. The ideas and scenario introduced here are based on discussions with N.Kishimoto (National Institute for Material Science), T.Iwayama (Aichi Kyoiku University), M.Terasawa (Hyogo Kenritsu University), K.Horioka (TIT), Y.Oguri (TIT), J.Hasegawa (TIT), and M.Kawai (KEK).

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