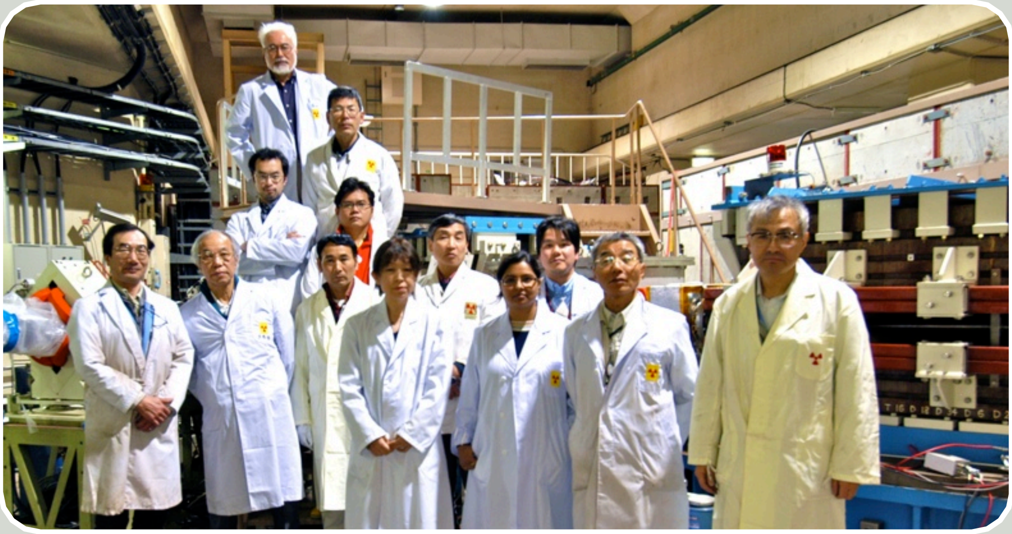
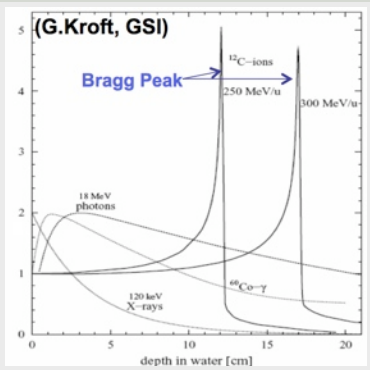


KEK's digital accelerator team members gather around the side of the KEK digital accelerator for a photo.

Particle accelerators are going digital

[Digital Accelerator, Medical, Biological, Environmental Applications]

The principle of KEK scientists' new invention, the induction synchrotron, was demonstrated in 2006, using the existing 12 GeV proton synchrotron at KEK. Now, the team is working hard to bring forth a digital accelerator for heavy ions based on the concept of the induction synchrotron, which they hope to have ready for use in a year's time. Read here about this new technology, and how the team developed the world's very first digital acceleration scheme.



When shot into a material, heavy ions deposit most of their energy immediately before they come to a halt. X-rays, in comparison, have broad distributions. This means that X-ray radiation therapy can cause damages to surrounding healthy tissues, and not just to target cancer cells.

Disturbing as it may sound, imagine cancer cells located near a human organ, cells that need to be treated. One of the most promising treatments is to irradiate cancer cells with high energy particles in order to ionize the DNA molecules in the cancer cells, breaking the molecules and killing the cells.

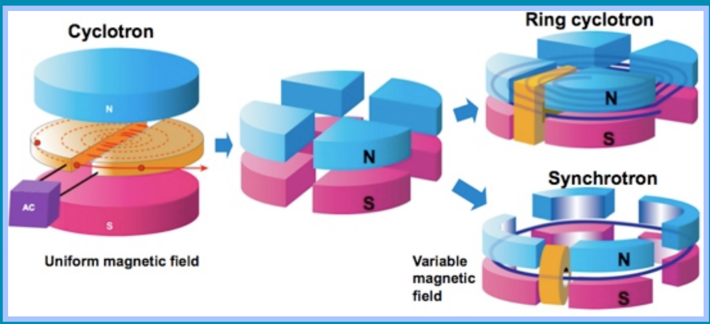
How exactly is that doctors can use radiation to damage the cancer cells but not the healthy cells around them? Particle therapy uses a property of particles called the Bragg peak of energy disposition. When a particle travels through a material, it deposits energy to its surroundings as it travels, before it comes to a complete halt. It turns out that ions lose most of their energy immediately before they come to stop. This property can be used to target cancer cells that are located at certain distance from the skin, without affecting healthy tissues on its way. Another well known radiation therapy for cancer, X-ray therapy, cannot do this. The energy loss spectrum is much broader (see plot) so that much of the energy gets absorbed by the surrounding, damaging unwanted regions. This feature remains the same for the recently developed technique called intensity-modulated radiotherapy.

The promising particle therapy treatment, however, is expensive. With current technology, this treatment requires expensive synchrotron accelerators. Two well known particle therapies are proton therapy and carbon therapy. To accelerate protons and heavier, more effective carbon ions in one accelerator requires a high power injector and a large accelerator ring, and therefore more expensive. What if an inexpensive and more compact device that can accelerate protons and carbons in one ring is readily available? This will equip every hospital to offer suitable treatment for different types of tumors.

With a new technology developed at KEK, this may soon be possible. The new technology is called a digital accelerator, and was issued a patent in 2007. This innovative device may revolutionize the century-old discipline of accelerator science. There are many possible applications, including medicine, biochemistry, environmental science, and stellar science.

A brief history of ring accelerators

The first man-made accelerator was Julius Pluecker's cathode tube, in which a discharge of electricity into rarefied gasses caused a fluorescent glow on the surface of a glass tube. Electrons were accelerated by an electrostatic voltage in the cathode tube. That was the original form of linear accelerator. Then in 1931 the first ring accelerator called cyclotron was developed. It drove charged particles in circular paths using a dipole magnet and alternating current voltage.



Ring accelerator evolved from cyclotron in which particles spirals out as they are accelerated by alternating current voltage in a uniform magnetic field. Synchrotron confines beam orbit at a fixed radius by adjusting the magnetic field. All ring accelerators nowadays takes a form of the synchrotron ring.

To accelerate particles to higher energies, the second-generation of ring accelerator called synchrotron, invented in 1945, drives particles with radiofrequency electromagnetic waves. Every ring accelerator around the world nowadays accelerates particles using radiofrequency waves. Then in 2000, an induction synchrotron now called a digital accelerator emerged as a new category of the ring accelerator, driving particles with induced electric pulses. The digital accelerator has the same acceleration scheme as the old induction accelerator, betatron, which drives particles with a voltage induced by a transformer, even though topologically two are completely different.

The original cyclotron used a magnetic field which is constant in time. This meant that as the speed of the particles increased the radius of the particle trajectories also increased. Ultimately, the physical size of the cyclotron magnets limited the maximum speed of the particles. In the second-generation accelerators, physicists made the magnetic field vary in strength to keep the radius of particle trajectories constant, independent of particle speed. Now magnets need not be solid disks, but instead arranged in a ring of certain radius. Radiofrequency drivers are inserted in several points on the ring. This is the synchrotron. Every operational high energy ring accelerator in the world drives particles using this basic design.

One problem with the radiofrequency scheme is that it requires a resonant device called radiofrequency cavity with a finite frequency bandwidth of a radiofrequency power amplifier. The frequency must be synchronized with the revolution frequency of an ion bunch in the ring. Generally, the dynamic range—the ratio between the largest and the smallest values—of the resonant frequency is of the order of 10. Because the highest radiofrequency is uniquely determined by an extraction energy, the lowest frequency available for acceleration should also be uniquely determined. The lowest frequency in turn determines the necessary revolution frequency (thus velocity and energy) of ion bunches at the injection. This requirement limits the shapes and sizes of a high energy accelerator. Before particles can enter the high energy ring, they must first be accelerated by a linear accelerator (an injector) and then by a low-energy accelerator ring (a booster). This is impractical for places like hospitals where the construction and operation cost and space are big issues.

Another problem comes from a fact that radiofrequency fields for acceleration provide two functions simultaneously rather than separately: acceleration and confinement of an ion bunch in the direction of motion. At the middle of each bunch would be the highest beam intensity region, because of the nature of radiofrequency capture. When this high local density reaches a charge density limit called a space-charge limitation, it is known that the space charge causes beam dispersion. It is therefore desirable to produce a bunch whose charge density would be uniform in the longitudinal direction, but a conventional radiofrequency synchrotron is just not made for such purpose.

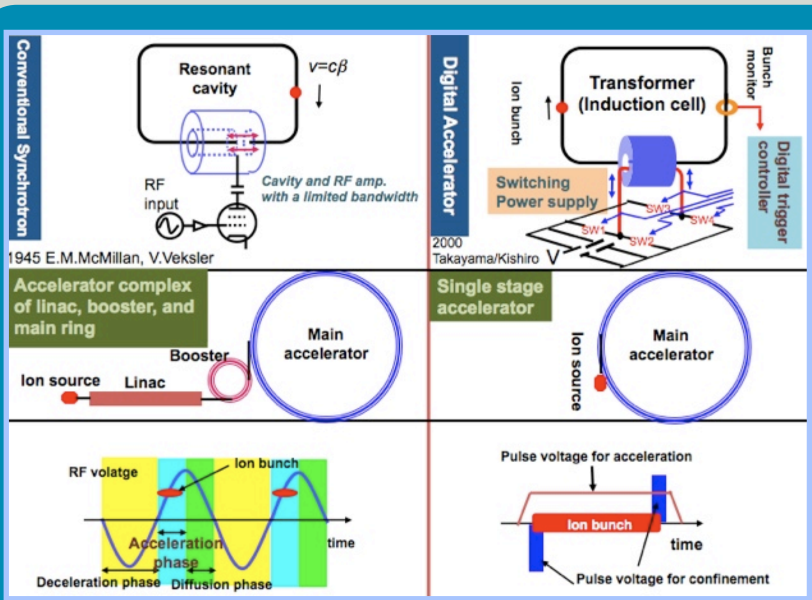
A digital accelerator might change all this. “In principle, a digital accelerator has no limit as to the type of ions and the range of energies it can accelerate,” says the leader of KEK’s digital accelerator group Prof. Ken Takayama. “Without requiring anything more than a single ring and an ion source, a digital accelerator should be able to accelerate any type of ion, from protons to uranium atoms, to any speed, from the speed of sound to the speed of light, ultimately speaking.”

There are many technical difficulties to overcome before such dream machine can become real. The Digital Accelerator team of 25 scientists from China, India, France, US, Malaysia, and Japan is taking solid steps forward. During the proof-of-principle experiment, which successfully ended in 2006, they made many important advances. Now the team is working to prepare the first available digital accelerator for users. They believe it will be ready for use in a year's time.

Proven principle of digital accelerator

Sense and response would be the right words to describe the principle behind the digital particle accelerator. Instead of radiofrequency cavities, a digital accelerator ring is equipped with devices called induction accelerating cells. Particles travel around the ring in a form of a bunch. When a charged particle bunch passes a beam sensor, the system picks up the signals and calculates the timing to generate the pulse voltage required to accelerate the bunch, and then produces the pulse voltage energizing a transformer.

The sense-and-response scheme has two big advantages over the radiofrequency scheme. First, because the particles in the ring automatically induce the necessary synchronized acceleration, a single ring can accelerate very slow ions to very high energy. Second, the scheme allows a vast range of freedom to control the bunch length. In the conventional radiofrequency scheme, the



Comparisons between conventional synchrotron and digital accelerator. A digital accelerator is simpler and smaller, as it requires only an ion source and a single accelerator ring. The acceleration scheme of a digital accelerator differs from the conventional one. A conventional accelerator uses a sinusoidal electrical field to accelerate particles, while a digital accelerator uses separately controlled electric pulses triggered by the circulating ion bunch itself. This gives the user increased freedom to choose the bunch length.

applied electromagnetic field has a sinusoidal shape in time. To keep particles confined in bunches during acceleration, only the rising positive portion of the radiofrequency voltage can be used. This portion accelerates particles in the tail of the bunch more than those in the head of the bunch, thereby forcing particles to group together. Since the rising positive part of the sinusoidal voltage is used to group particles together, the bunch length is controlled by the radiofrequency phase (timing) and the radiofrequency amplitude. In a digital accelerator, however, an accelerating voltage pulse and confinement voltage pulses are applied separately. By simply changing the voltage pulse width and the pulse duration between the barrier voltages, digital accelerator users can adjust the bunch length freely. (Since a digital accelerator would not waste three quarters of acceleration voltage like a radiofrequency accelerator does, it is also a power saver.)

Takayama and his colleague, the late Prof. Jun-ichi Kishiro, then at Japan Atomic Energy Agency (JAEA), jointly invented this idea. However, it was not until they conducted the proof-of-principle experiment that Takayama had realized the true potential of this concept. For the proof-of-principle experiment, they used KEK's 12 GeV proton synchrotron ring. On their first run, they accidentally sent very low frequency pulses. The shapes of the waveforms behaved exactly as the case for high frequency pulses. "In hindsight, it is obvious, but this accident is when we realized that using the digital accelerator, we can accelerate any ions, even slow and heavy ones, just out from the ion source," says Takayama. The digital accelerator is also called an All Ion Accelerator (AIA). This idea won the team the Japanese 21st Century Invention Prize for 2008.

The world's fastest switch

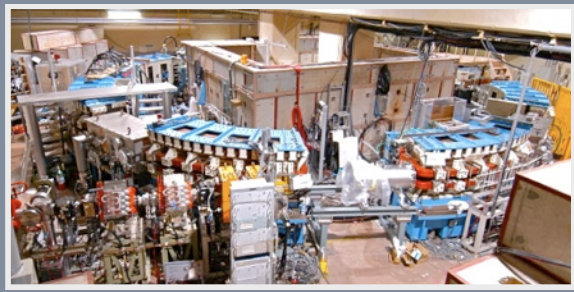
The key to building a working digital accelerator was to design the world's fastest high power electrical switches, ones that can flip an electric power of 30 kilowatt at the rate of 1 MHz. Particles in an accelerator usually travel near the speed of light, which means they travel around a ring of 300 meters in circumference a million times in second. This means that the switch must be capable of flipping at 1 MHz. The world has only seen switching device that could deliver up to five pulses with the 1 MHz separation, but only once every single second (1 Hz).

Takayama says that the fastest switching power supply wouldn't have been possible if not for the close collaborations with a pulse power industry and Tokyo Institute of Technology. "It was crucial to have arrived at a solution for a voltage unbalance among the switching elements connected in series, which are caused by the floating capacitances."

The problem with a high frequency switch is not only the switching circuit architecture itself, but also the heat produced by switching. 150 watt of heat is generated on each solid-state switching element of a 10 millimeter square, which is employed in the switching power supply capable of generating 2.5 kV. "We made many trial-and-loud blowups until we were able to get the switching heat under control," recalls Takayama. The team now has a copper heat sink with cooling water passages inside.

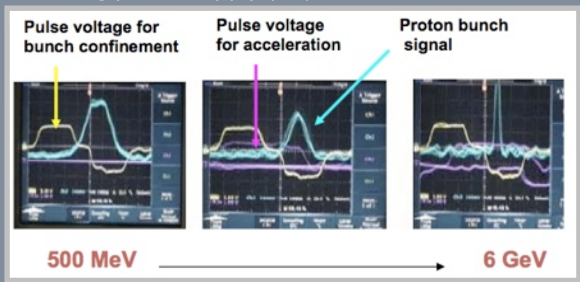
The quick bursts of current produced by the switches at such high frequency produces Eddy current, which heats up the magnetic material in the induction accelerator cells. "The cooling device for the cells is not anything you can take something available and modify a bit to fit the requirement," says Takayama. His student produced many prototypes, using oils for cooling.

The news of the completed 1 MHz switching power supply and the associated induction cells dazzled the world in 2004.

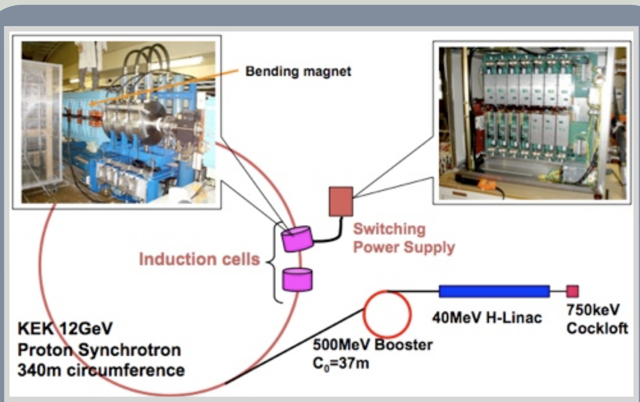


The digital accelerator ring at KEK.

From left: engineer Ei-ichi Kadokura, Dr. Taiki Iwashita, and Yoshio Arakida of KEK successfully developed the switching power supply (left).



In the proof-of-principle experiment, protons were successfully accelerated to 6 GeV.



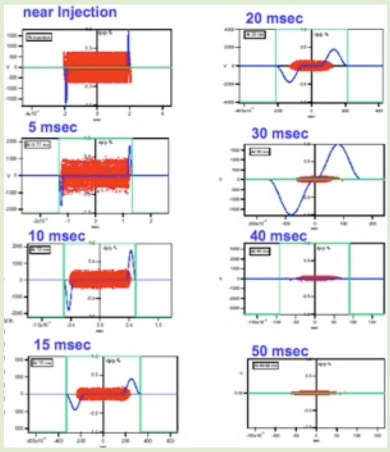
The proof-of-principle experiment was conducted using KEK's 12 GeV proton synchrotron ring with the newly installed induction cells and a switching power supply.

The next step to an all ion accelerator

The proof-of-principle experiment was done using protons. However, the team's ultimate goal is to make an all ion accelerator, one which can accelerate a range of ions from light ions (like protons) to heavy ions (like gold and uranium). The team's efforts are now concentrated on demonstrating the functionality of the digital accelerator as an argon accelerator.

"An argon ion is 40 times heavier than a proton, and so requires much more energy for the same amount of acceleration," explains Dr. Tanuja Dixit from the Society for Applied Microwave Electronics Engineering and Research (SAMEER) in India. Dixit came in KEK in 2005, and for her PhD, she developed the acceleration scenario for argon at the KEK digital accelerator, and designed the induction acceleration cell suitable for heavy ion acceleration. If argon capability is proven, any ions should automatically become available, provided that the ion source of interest is readily available.

To accelerate a heavy ion such as argon, Dixit found that she needed to divide the acceleration scheme into four phases. The first phase required induction cells arranged in parallel, and the second required cells arranged in series. The third phase required two 1 MHz induction cells to drive a beam with up to 2 MHz pulses, and the fourth phase required three cells to drive a beam with up to 3 MHz pulses. However, the heat issue limits the frequency of switching device to only 1 megahertz. "I was excited when I found that we could use multiple 1 megahertz cells simultaneously to produce higher frequency cells. The exciting thing about the digital accelerator is that it is so flexible," says Dixit.



To accelerate argons, simulation showed that the beam requires separate acceleration schemes for four different phases. Red: particles, blue: confinement voltage pulse, and green: acceleration voltage pulse.


Dr. Tanuja Dixit (center) from the Society for Applied Microwave Electronics Engineering and Research (SAMEER) in India and KEK engineer Mitsuo Hashimoto (left) have worked on the induction accelerator cells.

Designing the four-part acceleration scheme was a complicated task. "Each induction cell is given a set and a reset signals, and each signal comes from a switching supply that has 28 switching boards. Each board receives signals from the pattern controller. I made a number of wiring mistakes. There were wires everywhere," smiles Dixit.

Once Dixit finalized the acceleration scheme and finished wiring the induction cells, she then generated argon-like signals for equipment simulation. First, to check for the feasibility of the entire sense-and-response scheme, an arbitrary function generator device produces a waveform. The waveform triggers a signal to generate the voltage pulses to confine and accelerate the bunch. This work earned her the best student poster prize during the European Particle Accelerator Conference (EPAC) in 2008.

The team has also been preparing the argon ion source. An ion extraction test is currently underway, and the source will be installed in May. The team is looking forward to the beam commissioning this fall.

The many applications for a digital accelerator

"A digital accelerator would be useful in many research fields beyond medical applications," says Dixit. "You can find social relevance such environmental crops, and it would be satisfying? I would like to remain as long as possible in the field of accelerator science to see them."

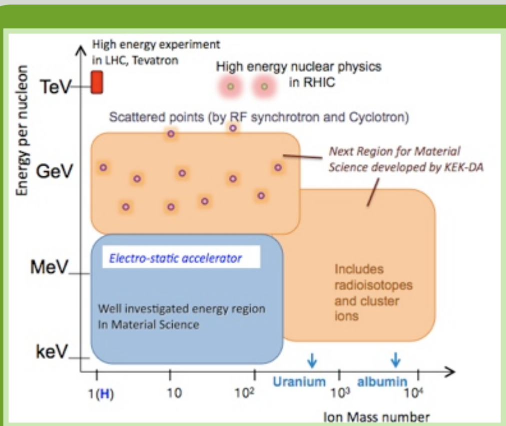
Using the intense, well-controlled heavy ion beam, scientists will be able to make mesh filters with nanometer-sized holes. Such a material could be used as a hemoglobin filter for blood. The intense ion beam can also alter material properties in diamond when shot into it to change the crystalline structure, making an insulator a conductor. This will allow production of three-dimensional nanometer-sized circuits. Applications of such circuit might completely change the industry of semiconductor devices, and may be useful for such future technologies as a quantum computer.

Because heavy ions transfer energy to their surroundings much more efficiently than gamma-rays or X-rays, a digital accelerator will also make an excellent tool to induce mutations, by breaking off the DNA's double helix. This has important applications in environmental science. Combining induced mutation with genetic engineering is a promising approach to developing crops with larger yields of food and biofuels.

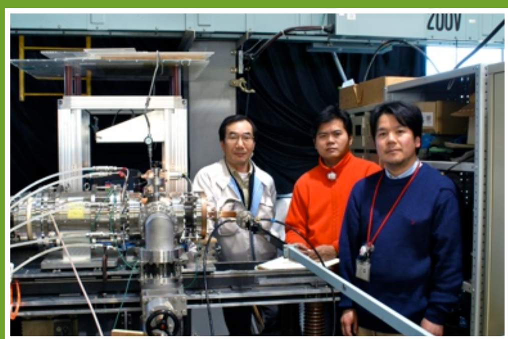
On the other hand, astrophysicists plan to use the digital accelerator technology to create high-temperature, high-pressure conditions like those in Jupiter's core. Biologists also plan to use the digital accelerator to produce the interstellar environment and explore how life can be formed in the interstellar environment of the cosmic rays and cosmic medium.

"The principle of our idea was proven in 2006, and in that I am satisfied," says Takayama. "Now, users are waiting to use our digital accelerator for their research. We are making every effort to provide this facility." Nearly a hundred users program members are eagerly waiting for time on the first available digital accelerator in the world.

The concept of the digital accelerator also may be applicable to future high-energy accelerators. Using a digital accelerator scheme, particle accelerators could work with very long bunches. CERN's LHC upgrade group has considered an idea called the superbunch. In this proposal, the bunch length would be increased from the current 5 centimeters to as long as 300 meters. This would improve the luminosity of the LHC by a factor of 10. Unfortunately, this would also produce so many undesired junk events that it would exceed the handling capability of the detectors, so that the idea is ultimately impractical. However, ideas like this abound, ready for future scientists to explore.



Digital accelerator will explore unknown region of materials science of heavier ions at higher energies.


From left: KEK engineer Teruo Arai, graduate student at Sokendai Leo Kwee Wah, and NAT engineer Koji Okazaki are in charge of the ion source.

Related Link:

[Super Bunch (Japanese)]

[CERN Carrier: Induction acceleration looks to the future]

[CERN Carrier: Rewriting the rules on proton acceleration]

Paper:

[Experimental Demonstration of the Induction Synchrotron]

[All-ion accelerators: An injector-free synchrotron]

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