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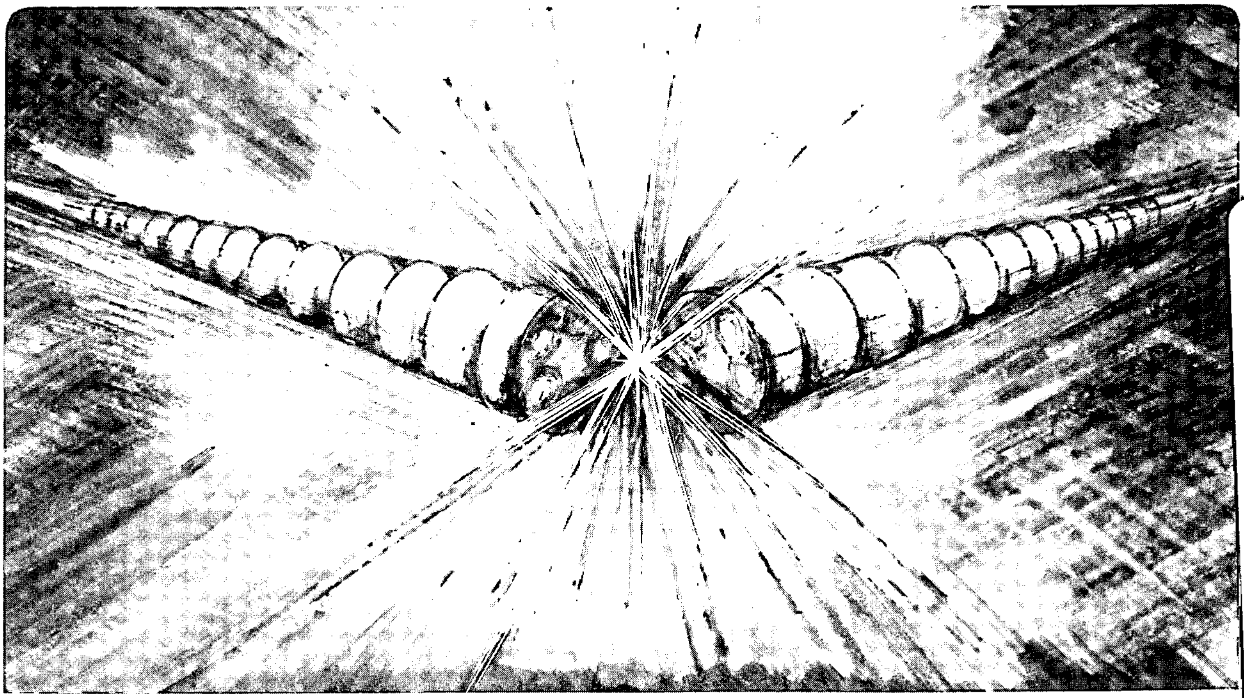

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REVIEW OF ION ACCELERATORS*

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The field of ion acceleration to higher energies has grown rapidly in the last years. Many new facilities, as well as substantial upgrades of existing facilities have extended the mass and energy range of available beams. Perhaps more significant for the long-term development of the field has been the expansion in the applications of these beams, and the building of facilities dedicated to areas outside of nuclear physics. This review will cover many of these new developments. Emphasis will be placed on accelerators with final energies above 50 MeV/amu. Facilities such as superconducting cyclotrons and storage rings are adequately covered in other review papers, and so will not be covered here.

Introduction

At the end of the first major growth-period in ion accelerator centers, around the early 70's, three types of accelerators predominated: Tandem Van de Graaffs, cyclotrons, and heavy-ion linacs. For the next ten years, relatively little growth occurred in the field, but in the last decade this growth has resumed at an extremely rapid pace. Factors leading to this growth are easy to pinpoint; breakthroughs in ion source technology, a dramatic increase in the interest in the field brought on by research results, the advent of beam-cooling techniques, and the realization that large proton-based facilities can be used for ion acceleration with relatively modest modifications.

Accelerator Developments

The nature of the technological advances has charted the course for the development of higher energy ion facilities. Although beam quality from Tandems is superb, their relatively low current, their cw nature, and poor energy performance for higher masses has made them generally unattractive as injectors for higher energy machines. Although recent advances in negative ion sources has greatly improved beam currents, it still remains that only one major facility (Brookhaven) uses a Tandem as its principal injector.

Perhaps the main reason for the rapid growth in the number of ion accelerator facilities has been the emergence of the ECR source. The reliability of this source, its good charge-state performance, and the promise of even better performance with on-going R&D programs, has made it the focal point of a large number of the new facilities coming on-line around the world now. This source has vastly improved the productivity and performance of existing cyclotrons (those with external injection capabilities); several of these cyclotrons have become injectors for other larger cyclotrons.

Heavy-ion linacs remain as the injector of choice for larger synchrotrons, owing to their high current, pulse timing and beam quality characteristics. In fact, the two remaining heavy-ion linacs built originally for research (SuperHILAC and UNILAC) have been converted into synchrotron injectors. Even with linacs, the ECR source is having a significant impact. Although these sources cannot increase the output energy of a linac as they can for a cyclotron, starting with a higher charge state allows simplification of low-beta sections and the removal of stripping stages. These improve system reliability, and beam quality and stability.

Electron-beam cooling has revolutionized the field of storage-ring physics. By producing beams of unheard-of quality, whole new vistas of beam-physics have been opened up. From fine atomic physics measurements to beam-crystallization possibilities, the imagination of a generation of physicists has been stimulated by the first results coming from these new storage rings.

The most dramatic advance of the past years has been in the energy of ion beams. After the demonstrations by Saturne, the Synchrophasotron and the Bevatron that ions could be accelerated in a proton synchrotron, and that the physics with these high-energy beams was interesting, energy barriers fell rapidly as first the AGS then the SPS accelerated beams up to mass 30 to their top energies. Within three years both these centers will have ion capabilities for all masses of ions, and within ten years both plan to have colliding beams in the hundreds to thousands of GeV/amu range. The physics that will emerge from these ultra-relativistic collisions we can enjoy speculating about.

Research Fields

Interesting, too, has been the evolution of research fields accompanying these accelerators. Nuclear physics has been the prime motivator (and funder) of the greatest majority of these facilities. But, other fields are developing, and are absorbing more and more of the available accelerator resources. Atomic physics, astrophysics and space science, and very visibly now medical science communities are actively using ion beams in their research.

Nuclear physics studies have evolved smoothly from lower energies, with established programs extrapolating their measurements to higher energies. Thus, reaction mechanism studies have moved from the region where the mean-field approximation is valid into transition areas where multi-fragmentation dominates, and through to where hydrodynamic flow of nucleons characterize the final state. Nuclear structure studies have moved to the outer reaches of the chart of nuclides, probing the neutron and proton drip lines, as well as searching for superheavy islands that might be produced by means of exotic reactions. At energies around 1 GeV/amu studies of the nuclear equation of state are of greatest interest. Not only of interest to nuclear physicists, knowledge of the equation of state can shed light on stellar interiors, neutron stars and supernova explosions. At the highest energies it is postulated that sufficient energy density can be created in colliding nuclei to cause quark deconfinement and so study basic parameters of nature that have not existed in the Universe since the Big Bang. Heady stuff!

Atomic physics studies with energetic ion beams are noteworthy because given sufficient energy any ionic state of any atom can be created and studied. At around 600 MeV/amu it is possible to strip all of the electrons off of a uranium atom. Thus, for instance, Lamb-shift measurements have been performed on hydrogenic uranium atoms, probing the validity of QED in what are perhaps nature's strongest electric fields. While perhaps not as spectacular, much information is being obtained from highly ionized systems, of relevance to basic atomic processes as well as to stellar interiors.

Intermediate energy ion accelerators have proven to be excellent simulators for galactic cosmic rays. Programs have been in place for some time for calibration of satellite instrumentation to better characterize this spectrum. Recently, an important concern has arisen, namely that with the expectation of lengthy space missions by astronauts in the not-too-distant future, what will the impact of these cosmic rays be on the physical well-being of these space-travellers. Based on our knowledge of the galactic cosmic ray spectrum, it has been calculated that on a three-year mission outside of the earth's protective magnetic field, approximately 30% of the DNA in an astronaut's body will be damaged by a heavy ($A > 15$) cosmic ray. The biological effects of this are not well known at this time. How much repair occurs, the mutation rate caused by faulty repair, and outright cell-death, are all questions that must be researched. Short-term and long-term effects of this type of low-level continuous exposure must be determined to assess the risks of sending man on long space missions.

The biological effects of large doses of radiation have been much more thoroughly studied. In fact, charged-particle beams are emerging as a preferred modality for cancer radiotherapy. The energy-deposition characteristics of a charged-particle as it penetrates and stops in tissue is extremely favorable: as $dE/dx \approx 1/E$, the greatest deposition of energy occurs in the last millimeter or two prior to the stopping of this particle. By adjusting a particle beam so that this "Bragg peak" occurs inside a tumor, selective damage can be done to the tumor while sparing the normal tissue around it. Radiation therapy with proton beams has taken place for almost 40 years now, but the lack of adequate accelerator technology has prevented its widespread application. This seems to be changing now, as several dedicated medical accelerator centers are now being built around the world. Particles heavier than protons have some definite advantages, too: they undergo less multiple scattering, and so their stopping point in tissue is better defined (a point-like neon beam will spread 3 mm after penetrating 20 cm in tissue, compared to 25 mm for a similar proton beam). As alluded to in the last paragraph, the biological damage is more severe for heavier ions, too, with possibilities of more effective treatment of traditionally radio-resistant tumors. This last point is still being actively researched, but practitioners are optimistic about future prospects.

We will now turn to the main subject of this paper, namely a review of ion accelerator facilities. This review is limited to accelerators producing beams of ions of A >1 at over 50 MeV/amu. As superconducting cyclotrons are covered in a review by Schreuder, we shall not discuss the MSU, Milan (Catania), Texas A&M or other such machines. With regard to storage rings, emphasis will be placed on those that provide extracted-beam capability. All these rings are covered in more detail in Jaeschke's review paper dedicated to storage rings elsewhere in these proceedings.

Cyclotrons

There are seven major cyclotron facilities in the world today with heavy- and light-ion capabilities. GANIL (Caen, France) is today without doubt the world's most active center for nuclear physics research at the lower end of our energy range. With its two K400 coupled cyclotrons and its flexible injector complex of smaller cyclotrons and different ion sources, its highest energies are 95 MeV/amu for carbon and now 29 MeV/amu for lead. This facility is actively involved in nuclear structure and nuclear reaction work. Of particular note is their program with exotic secondary beams centered on the LISE spectrometer, that is actively probing the limits of nuclear stability at the proton and neutron drip lines. GANIL has just completed an upgrade project which improves the intensity and energy performance of their cyclotrons for the heaviest masses. The key element of this upgrade has been the installation of an improved ECR source (CAPRICE-type), capable of producing over 100 enA of Pb^{23+}. A new source, ECR4, operating at 14.5 GHz is under development and is expected to yield even further performance improvements. Upgrades of the transport lines, bunchers and the CO2 injector cyclotron have contributed to these performance gains. A long-term project of a new superconducting booster cyclotron, designated CSS3 is being contemplated; it will boost final energies into the 100's of MeV/amu.

RCNP (Osaka, Japan) is the newest project on the list. The new K400 six-magnet separated-sector cyclotron is currently under construction, the magnets are in the final assembly stages in the accelerator vault. Injected by the presently-operating K180 AVF cyclotron, this accelerator will concentrate on light-ion ($A \leq 40$) studies. The vacuum in this accelerator restricts operations to ion species that are fully-stripped, not a problem for all of the presently-contemplated research programs. A large experimental hall features a long (over 50 meter) neutron time-of-flight line and a recirculating ring transport system to bring the beam repeatedly through a thin target at a large spectrometer. Although not planned as a cooler ring, it certainly has the potential for upgrading to one sometime in the future. A transport line has been designed to bring a 250 MeV proton beam to an area outside the present building reserved for a future radiotherapy medical center. Construction is progressing very rapidly, they are expecting first beam in August, 1991.

The RIKEN Ring Cyclotron (Wako, Saitama, Japan) has been in operation now for over three years. A four-magnet (straight-edge) separated-sector K540 cyclotron is injected by the RILAC linear accelerator and an new K70 AVF cyclotron. Currently, ions to Xe have been accelerated, at a maximum Xe energy of 8.5 MeV/amu. With a planned injection upgrade, uranium at 20 MeV/amu is expected. The RILAC injector is a novel, variable-frequency Wideröe accelerator (the world's only such machine). Frequency tuning, from 17 to 45 MHz is achieved by adjusting the length of tuner-stems inside the six linac tanks. This tunability allows a wide range of q/A values, down to a low of 1/20. This accelerator services its own low-energy experimental area, delivering beams from 0.8 MeV/amu (for the heaviest, q/A = 1/20 beams) to 4 MeV/amu. The K70 cyclotron, axially injected by a 10 GHz ECR source provides the bulk of the main-cyclotron light-ion injection needs. A recently-acquired (from Grenoble) permanent-magnet ECR source will soon be added to the front-end of the RILAC, boosting the output energy of this injector by allowing it to run at its higher-frequency range. This will result in 20 MeV/amu uranium beams, and beams over 50 MeV/amu in the mid-mass region. Research activities at this accelerator cover a wide range of applications, including nuclear physics, atomic physics, nuclear chemistry, material sciences and radiobiology. This reflects the broad base of research programs at the RIKEN laboratory.

The Heavy-Ion Research Facility at Lanzhou, China (HIRFL) is a K450 four-sector cyclotron injected by a K69 SFC cyclotron. The internal PIG source provides beams of argon which are accelerated to 50 MeV/amu. An ECR source, currently under construction, is expected to boost system performance up to 7 MeV/amu for mass ≈200 ions. A single large experimental hall houses at least eight experimental stations, including scattering chambers, an on-line isotope separator, and various spectrometers as well as atomic physics and radiochemistry facilities. An active user program is in place, and interest in applying for beam-time is always welcome.

Other noteworthy cyclotron facilities include the NAL center in Faure, South Africa, a K200 cyclotron mainly used for proton research. A good portion of their program is dedicated to medical treatments, currently with fast neutrons, but soon to be with the primary proton beam. The Indiana Cyclotron (IUCF), a K215 machine in operation for many years now, has recently installed a cooler ring, the only one of its kind in the United States. Although primarily concentrating on protons (polarized and otherwise), ions up to Li are available. Plans are also being developed for a medical treatment program with their proton beam. The Gustaf Werner K200 synchrocyclotron, at Uppsala, Sweden, has been recently rebuilt from its original 1951 form, incorporating a sector-focused design. An external (6.4 GHz) ECR source will provide ions to Kr for acceleration in the cyclotron in the near future. One of the early leaders in proton radiotherapy, it is anticipated that the treatment program will resume after its ten-year hiatus during the cyclotron rebuilding project. Crown-jewel of this facility, however, is the soon-to-be completed CELSIUS ring, to be briefly discussed below.

Medium Energy Accelerators

In this section we will visit twelve medium energy accelerators and storage ring facilities. Again, we are limiting ourselves to ions (A > 1) at energies above 50 MeV/amu ($B\rho$ > 2.0 T-m). Thus, such facilities as ASTRID, CRYRING and TSR, very exciting but lower energy centers, will not be discussed.

Storage Rings

An excellent review by Jaeschke in these proceedings covers most of the features of ion storage rings, we will only briefly talk about them here. The IUCF Cooler is now operational, electron cooling has been accomplished, as well as the first experimental verification of the Siberian Snake concept for preserving beam polarization through synchrotron depolarizing resonances. Internal target experiments are starting, utilizing a vapor target. A dust target is also under development. The CELSIUS ring is an excellent example of a recycled accelerator. Built first as the g-2 experiment at CERN, it was later converted into ICE for the development of stochastic cooling. Now in its third life, it has been moved to Uppsala, where it is injected by the Gustaf Werner synchrocyclotron. It will be used for cooling experiments as well as for atomic physics and nuclear studies with thin targets. While the initial studies will be done with protons, an ECR source is being developed, giving this ring the capability for heavy-ion research. Neither of the two rings above, by the way, are provided with an extraction system.

The next four storage rings do have extraction systems, allowing both circulating-beam and external fixed-target experiments. The TARN II ring at INS, Tokyo is an outgrowth of the highly successful TARN I experiment. TARN I demonstrated stochastic cooling and multi-dimensional phase-space stacking, while the larger TARN II, in operation for almost a year now, is being used mainly for electron cooling experiments. The slow resonant extraction system has been recently commissioned. The LEAR ring, primarily used now for anti-proton physics at low energies, has recently seen use with oxygen ions. These ions have been injected, electron cooled and stacked, then accelerated to maximum energy (400 MeV/amu) and extracted for a Bragg-peak demonstration experiment.

The ESR at GSI is now in the early commissioning stages. An argon beam has recently been stored, and successfully cooled at an energy of 98 MeV/amu. This ring will be used as a part of the highly flexible GSI accelerator complex, for accumulation and cooling of radioactive ions produced in the Fragment Separator line, for stripping and reinjection into the SIS ring with a fast-extraction system, for stochastic and electron cooling experiments at high energies with very heavy ions, and for internal gas-jet target experiments. A slow extraction system also allows the ESR to be used as a stretcher for fixed-target experiments in the main experimental hall.

Finally, the COSY ring at Jülich is in mid-construction. The building is ready now, and magnets will soon be installed in their positions in the ring. Noteworthy because of its long (40 meter) straight sections, this ring will have both electron and stochastic cooling capabilities. Meson physics experiments, both internal and external are planned; the ultraslow extracted beams being transported to the high momentum resolution spectrometer called BIG KARL. The JULIC injector-cyclotron is being upgraded to more reliably and higher intensity. This cyclotron produces H_2^+ beams for stripping injection into the COSY ring. An existing 16 GHz ECR source will be added at a later date to provide ions up to mass 40, again relying on stripping injection.

Synchrotrons

Six heavy-ion synchrotrons share the stage in the medium energy regime. They will be listed in order of ascending $B\rho$. The first in the list, HIMAC, being built now in Chiba, Japan, is particularly noteworthy as it is the first heavy-ion synchrotron dedicated exclusively to medicine. This complex, now in its initial construction stages, features an RFQ-Alvarez injector linac scheme, with a PIG and an ECR as ion sources. Beam is injected at 6 MeV/amu into one of two identical synchrotron rings separated by ten meters of vertical elevation. Beams up to 800 MeV/amu for $q/A = .5$ ions are delivered to one of three treatment rooms, one with a vertical beam, one with a horizontal beam, and one with both horizontal and vertical beams. Radiobiology and test-beam irradiation areas are available as well. Building a facility with two rings has several advantages. A single treatment can be delivered with twice the dose-rate; simultaneous treatments in different rooms can speed the patient flow; added reliability through redundancy can make the radiotherapists more comfortable; bumping of the power grid can be minimized, as power can be taken from the grid into one ring as it is being given back by the second. In addition, the second ring can be used as an accumulator for secondary beams. Although slow extraction will be used principally, a fast-kicker system is planned for inter-ring transfers. Conventional construction is well underway, and technical components are being fabricated. Completion is expected in three years, with the first patient being treated on November 1993.

It should be pointed out that although HIMAC is the first heavy-ion facility being built exclusively for medicine, it is not the first dedicated synchrotron. This honor belongs to the Loma Linda proton facility, currently being commissioned at the Loma Linda Medical Center Hospital just outside of Los Angeles, California. This 250 MeV synchrotron, built by Fermilab and shipped to Loma Linda, delivers beams to four treatment areas, three of them equipped with isocentric gantries capable of delivering beam into a patient from any angle by rotating the beam-delivery system around the patient in a full vertical circle. Their first patient treatment is expected in mid 1990, and they anticipate when fully operational to treat about 1000 patients per year.

SATURNE has been delivering light-ions since it was upgraded from SATURNE I to SATURNE II over ten years ago. Since the commissioning in 1987 of MIMAS, the low-energy accumulator/booster ring, performance of the facility has improved dramatically. Now it is capable of producing beams up to krypton at 700 MeV/amu, as well as high-intensity polarized proton and deuteron beams at 3 GeV. In MIMAS, 133 turns are stacked in synchrotron phase-space by a betatron deceleration scheme; this injection scheme is designed to work equally well with any one of the three different injectors, each with a very different type of pulse structure. Extremes of injection requirements are given on one side by Dione, an EBIS-based injector which produces heavy ions in microsecond bursts at 50 millisecond intervals, while on the other side Hyperion, the polarized-ion source, produces beam continuously, filling MIMAS in about 1 millisecond. Beam is accelerated to 12 MeV/amu and kicked over to the synchrotron for final acceleration. With its collection of high precision spectrometers, this facility has concentrated heavily on nuclear structure studies and mesonic resonances in nuclei. Noteworthy are the heavy-ion induced giant dipole resonance experiments, requiring superb beam quality and spectrometer resolution. These studies cannot be done anywhere else in the world.

The new flagship of the medium-energy heavy-ion fleet is SIS-18 at GSI, Darmstadt. This 18 Tesla-meter synchrotron serves as the source of ions in the GeV/amu energy range to a most flexible complex of experimental opportunities. Beams can either be sent directly to the experimental area, about five target stations are presently planned; or they can be injected into the ESR ring for storage or cooling; or into a production target for secondary beam production. The secondaries can be analyzed in the Fragment Separator line and also sent either directly to an experimental station or to the ESR for accumulation and cooling. In the ESR beam can be used directly for internal beam experiments or extracted and reinjected into the SIS ring. In this way fully stripped uranium can be reaccelerated in SIS to a maximum energy of 1.4 GeV/amu. A wide range of experimental programs are planned at this facility, from nuclear equation of state studies to atomic physics with highly-stripped very heavy ions. An active radiobiology and biophysics research effort is also underway. Ultra-short extraction of the highest-intensity beams is also used, for studies of beam-induced plasma heating and other research associated with heavy-ion-induced fusion.

The SIS ring is injected by the UNILAC, one of the two existing linacs capable of delivering beams of the heaviest elements above the Coulomb barrier. The injection energy is selected at 11.4 MeV/amu, somewhat below the top energy available from the linac. Currently, two PIG sources on high-voltage platforms feed the first Wideröe tank, an upgrade under construction now will have an ECR source, RFQ and IH linac feed high-mass ions directly into the second stage of the UNILAC. This upgrade will improve the efficiency and stability of highest-mass beams in the UNILAC, and will improve the flexibility of the injection system. The SIS complex is capable of "supercycle" operation, with as many as 30 different modes, different ion/energy/beam-line combinations all sharing beams in a sequential fashion. An upgrade planned in about three years will provide a low charge-state very high current front-end to the UNILAC, and will drive beam currents in SIS up to their space-charge limits. Uranium beams as high as 10^{10} ions per pulse will be accelerated. The SIS/ESR complex is now in full commissioning status, and although some teething problems have been encountered with the slow-extraction system, overall system performance has been excellent.

The BEVALAC at Berkeley has pioneered much of the field of medium and high energy heavy ion research. From 1982 to 1989 it was the only machine in the world with GeV/amu uranium beams, and it in fact has provided much of the impetus for the growth of the field. The heavy ion career of the Bevatron began in 1974 when the Transfer Line was built connecting this weak-focusing synchrotron to the SuperHILAC, the world's other uranium-above-the-Coulomb-barrier linac. With a maximum rigidity of 19.2 T-m, beams of $q/A=.5$ ions reach an energy of 2.1 GeV/amu. Typical uranium charge state run is 68+, produced by stripping at the 8.5 MeV/amu output energy of the SuperHILAC. A second injector produces light-ion beams ($A \leq 40$) at 5 MeV/amu. These two injectors can operate simultaneously, giving rapid ion-switching capability. All accelerator system parameters can be changed in under one minute, allowing sharing of beams between two programs on a short time scale. This is useful for interleaving the patient radiotherapy program, which runs every day and absorbs over 30% of the total beam-time, with nuclear science experiments. In addition to these two programs, atomic physics and space-science research is actively pursued.

Two machines in the Soviet Union round out our list. The ITEP synchrotron in Moscow, a 9 GeV proton machine, and long one of the USSR's prime proton-therapy centers (with slow-extracted beams at 200 MeV), is currently commissioning an ambitious heavy-ion project. Beams from a MEVVA ion source (relatively low charge-state, but high current) are run through a novel two-gap resonator tank, bent through 270° and brought again through the same resonator on a perpendicular path. These two passes bring U^{5+} to 200 keV/amu. These ions are stripped to 15+, and are injected into the ITEP synchrotron, with a newly-installed 10^{-10} torr vacuum system. They are accelerated to 3 MeV/amu, kicked out through a stripper (45+) and into a small ring, then re-injected into the main ring for final acceleration to the final 1.2 GeV/amu energy range. Most of the components are in place, and are being brought on line at this time. It is anticipated that the medical program will move to a new dedicated proton medical center to be built nearby, so the ITEP complex can be used exclusively for nuclear research with heavy ions.

The Synchrophasotron, the world's largest still-operating weak-focusing synchrotron has an active heavy ion program. Vacuum in the accelerator prevents accelerating any ion that is not fully stripped, so the heaviest ion currently available is Mg^{12+}. This ion can be accelerated to a maximum energy of 4.2 GeV/amu. Two injectors are used, a 5 MeV/amu linac with a CO$_2$ laser ion source for light ions (mainly carbon), and an EBIS source on a high-voltage platform injecting directly into the synchrotron for the heavier ions. A long-planned upgrade called the Nuclotron is based on a novel superferric superconducting magnet design, and is currently awaiting funding.

High Energy Facilities

Two of the world's great high-energy physics centers have jumped headlong into the heavy-ion field. Brookhaven and CERN have both demonstrated light-ion acceleration and have performed fixed-target experiments. Both Laboratories are moving rapidly towards heavy-ion fixed target capability, and then on to colliding beam rings at very high energies.

At Brookhaven, a 700 meter transport line was built to connect the Tandem accelerators to the AGS. The Tandems are capable of delivering beams up to silicon as fully-stripped ions at 6 MeV/amu. These are multi-turn injected into the AGS, accelerated (with two different rf systems) and extracted at 15 GeV/amu. The Tandem serves very admirably as an injector for the AGS, recent advances in negative ion source technology yield excellent beam currents, and the extremely low emittance of the Tandem beam allows efficient phase-space stacking in the AGS. Approximately six weeks a year, for the past two years now, have been dedicated to ion running.

Heavier-ion capability will be provided when the Booster is completed. This 17 T-m ring will take 14+ gold ions from the Tandem at 1 MeV/amu and accelerate them to 72 MeV/amu. In the transport to the AGS they will be stripped to 77+, then accelerated to 10.4 GeV/amu. The Booster is approaching the end of its construction phase, and will be commissioned in about a year's time. It will also serve as a high-intensity injector for polarized beams into the AGS for the ongoing high-energy physics programs there.

The culmination of the Brookhaven effort will be the RHIC project. Two intersecting storage rings built in the existing tunnel from the ISABELLE project will allow collisions of counter-rotating 100 GeV/amu gold beams at four intersection regions. Proton collisions at 250 GeV per beam will also be possible. Construction start is expected in 1991, funds have been asked for by the Department of Energy, and are expected to be approved by Congress this summer. A six-year construction is anticipated, first collisions are expected in 1997. Project costs are greatly helped by the availability of the tunnel and the large refrigeration plant. The design for technical components is well along, magnet parameters are set extremely conservatively (operating field is 3.5T), and prototype magnets have all trained to fields about 130% of the required value. Confidence is high at Brookhaven that no major technical problems will be encountered.

At CERN oxygen and sulphur ions have been accelerated to 200 GeV/amu and used for fixed-target experiments. Key to this accomplishment has been the ion injector built in 1986 by a joint GSI-LBL-CERN collaboration, and the subsequent purchase of a more powerful ECR source in 1987 for sulphur operation. The ECR source is coupled to an RFQ located at the entrance of the CERN Linac I Alvarez. O^{6+} (S^{12+}) ions from the source are accelerated to 12 MeV/amu in the linac, stripped and injected into the PSBooster, then at 260 MeV/amu to the PS, and finally at 10 GeV/amu to the SPS. In addition to the source and RFQ, vacuum and rf improvements were required for the Linac, and beam-monitoring instrumentation had to be developed for the very low intensity ion beams. Tuning of the accelerator complex for sulphur involved using oxygen as a tracer, accelerating both ion species through to the PS where fine tuning of beam orbits at transition allowed the selection of one ion or the other (due to their very small nuclear binding-energy difference) for further acceleration.

The excitement created by the physics results of the first ion runs has led to serious planning for an upgrade to lead ions. The current design calls for a high-frequency (18-20 GHz) ECR source producing Pb^{25+}, a 100 MHz RFQ followed by a new linac to bring the ions to 4.5 MeV/amu. Stripped first to 53+ then to 82+, they go through the PSB, PS, and SPS. Vacuum upgrades are needed in the PSB and PS. Beam levels are expected to be around 4 x 10^8 ions per SPS pulse, well above experimenter requests. This project should start within the next few months, and lead beams should be available in about three years.

With growing enthusiasm for LHC, the inevitable question arises as to how one would place lead ions in this collider. Much higher intensities of lead ions will be needed, and well-defined upgrade paths have been outlined, dealing with source improvements, as well as creative use of the accumulator and cooler rings available at CERN. Under most optimistic conditions, LHC filling in as little as 8 minutes is predicted. With lead or uranium ion collisions at energies of 3 TeV/amu per beam, something interesting is bound to happen!

Summary and Conclusions

With the explosive growth of the field of ion acceleration, and the large number of new construction and upgrade projects, one can ask where the field is going. In fact, certain very significant trends are beginning to emerge that will probably show what this direction will be.

First of all, nuclear physics has been the chief provider in this field, and will probably remain so for some time to come. Within nuclear physics, though, it is clear that the community is moving inexorably to higher energies. Truth is, the excitement of hunting for the deconfined quark is a holy grail that is drawing researchers from lower energies. The corollary of this move is that there will be a decrease in the emphasis on programs at lower energies. Support for the high energy programs will not come from new money in the field, there is very little of that, and already the economic pinch of this change in emphasis is being felt in many areas. As a consequence, one is seeing many of the traditional nuclear physics laboratories branching out into other fields in search of new communities (and new funding sources) to keep their facilities operating at high capacity. To date the non-nuclear-physics activities are for the most part still a small fraction of the overall research program at these facilities, but the trend is definitely upwards, and the disproportionate interest in these outside activities clearly shows that facility managers are hoping that these programs will in fact grow and contribute significantly to the scientific well-being of their laboratories.

One area that is bucking this trend towards higher energies is the low-energy storage ring. These rings have opened wide the eyes of the scientific community with a bright array of new research opportunities. Led by the TSR at Heidelberg, the possibilities for ultra-precise measurements have revealed a whole new arena of possibilities in atomic physics and accelerator physics, opportunities to take a fresh look at many well-established concepts with the expectation that some interesting surprises will emerge. Laser-cooling, beam-crystallization, free-electron - ion interactions are currently among the hottest topics being pursued. It is unlikely that the interest in these rings will peak for another ten years or more.

Applications that are emerging as the brightest prospects for future use of ion accelerator facilities are in the areas of industry and medicine.

Industrial uses to date have concentrated on micropore filter fabrication, and single-event upset studies in computer chips. Radiation-hardening of electronic components is of critical importance, both for space and terrestrial environments. Testing of these chips in charged-particle beams is being performed at a fairly large number of accelerators now. Biological studies of low-dose exposures anticipated in interplanetary space travel are also rising as a necessary research program. As an interesting aside, computer chips are now sufficiently sophisticated that one can characterize their response to radiation in the same framework as biologists use for cell studies, so one might say that biological research of both carbon-based and silicon-based systems (might we say "life"?) will be actively pursued in the future.

The most exciting application in my mind is in the field of medical treatments. The superb dose-localization, and potential for gains from the higher biological effectiveness of highly-ionizing radiation have opened new horizons in the potential for radiation treatment of cancer. The fact that hospital-based accelerator systems are currently being built, even with our relatively unsophisticated state of technology, is a clear indication that the medical community is beginning to believe that charged-particle therapy is the modality of the future for radiation therapy. The challenge to the accelerator community is to improve the state of accelerator technology to where heavy-charged-particle sources at the required energies (several hundred MeV/amu) can be provided in compact, reasonably-priced, easy-to-operate, and highly-reliable packages. A good example to point to as a success story is in the field of electron linacs. These compact high-gradient disc-and-washer structures have spearheaded the advance in radiotherapy with x-rays by increasing the x-ray beam energy from 200 keV (called "orthovoltage") to several tens of MeV ("megavoltage x-rays"). These compact linacs typically fit on the gantry head of a therapy unit and can be rotated around the patient to bring the beam in from any angle. Although ion accelerators will never approach that size (with foreseeable technology, at any rate), significant improvements in reliability and beam-delivery flexibility, as well as cost-optimization can make accelerator packages much more attractive to the medical community.

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Table I - Cyclotrons (Non-superconducting)

Facility	K_{max}	E_{max} light ion	E_{max} heaviest ion	Research concentration
GANIL Caen, France	380	95 MeV/amu (Carbon)	29 MeV/amu (Lead)	Nuclear structure Nuclear reactions Radioactive beams Atomic physics
RCNP Osaka, Japan	400	400 MeV (Proton)	100 MeV/amu (Neon)	Nuclear structure Nuclear reactions
RIKEN Wako, Saitama, Japan	540	135 MeV/amu (Carbon)	20 MeV/amu (Uranium)	Nuclear structure Nuclear reactions Radioactive beams
HIRFL Lanzhou, China	450	125 MeV/amu (Carbon)	7 MeV/amu (Tantalum)	Nuclear studies Industrial Atomic physics
Gustaf Werner Uppsala, Sweden	200	200 MeV (Protons)	10 MeV/amu (Krypton)	Nuclear physics Medicine
IUCF Indiana, USA	215	215 MeV (Proton)	50 MeV/amu (Lithium)	Nuclear structure (medicine)
NAL Faure, So Africa	200	200 MeV (Proton)	50 MeV/amu (Helium)	Nuclear structure Medicine

Table II (a) - Medium energy accelerators - Storage Rings

Facility	Kind	$B\rho_{max}$	E_{max} heaviest ion	Research concentration
IUCF-Cooler Bloomington, Indiana	Storage Ring (no extraction)	3.5 T-m	Li - 100 MeV/amu	Cooling Polarization Internal target nuclear studies
CELSIUS Uppsala, Sweden	Storage Ring (no extraction)	7.0 T-m	Kr^{30+} - 250 MeV/amu	Cooling Atomic physics Internal target nuclear studies
TARN II Tokyo, Japan	Storage Ring	6.1 T-m	Ar^{18+} - 330 MeV/amu	Cooling Nuclear studies
LEAR CERN, Switzerland	Storage Ring	6.4 T-m	O^{8+} - 400 MeV/amu	Cooling P-bar physics Nuclear studies
ESR Darmstadt, Germany	Storage Ring	10.0 T-m	U^{92+} - 560 MeV/amu	Cooling Atomic physics Radioactive beams Internal target nuclear studies
COSY Jülich, Germany	Storage Ring	11.0 T-m	Ar^{18+} - 820 MeV/amu	Cooling Nuclear studies

Table II (b) - Medium energy accelerators - Synchrotrons

Facility	Kind	$B\rho_{max}$	E_{max} heaviest ion	Research concentration
HIMAC Chiba, Japan	Synchrotron (2)	10.0 T-m	Ar^{18+} - 680 MeV/amu	Medicine
Saturne Gif-sur-Yvette, France	Synchrotron	13.0 T-m	Kr^{30+} - 700 MeV/amu	Nuclear studies
SIS-18 Darmstadt, Germany	Synchrotron	18.0 T-m	U^{78+} - 1 GeV/amu	Nuclear studies Radioactive beams Biomedical studies
Bevalac Berkeley, California	Synchrotron (weak focusing)	19.2 T-m	U^{68+} - 960 MeV/amu	Nuclear studies Biomedical studies Atomic physics Space sciences
ITEP Moscow, USSR	Synchrotron	33.0 T-m	U^{45+} - 1.2 GeV/amu	Nuclear studies Radiotherapy (protons)
Synchrophasotron Dubna, USSR	Synchrotron (weak focusing)	33.6 T-m	Mg^{12+} - 4.2 GeV/amu	Nuclear studies

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