ION ACCELERATORS AND STORAGE RINGS

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In the field of low and medium energy ion acceleration, continuous progress is observed, with ECR ion source developments playing an important role. Enormous steps towards ultra relativistic energies have been made in the high energy range. By using existing proton facilities, energies up to 200 GeV/u can be achieved for light ions. Similar, and even much higher energy beams are considered in near future for the heaviest masses.

A whole generation of low and medium energy ion cooler-storage rings are under construction or have already started commissioning. These rings, as well as a new synchrotron/storage ring combination, offer completely new experimental possibilities in the fields of atomic and nuclear physics in the MeV/u to GeV/u range. Also, studying cooling techniques for ions seems to be very attractive. A rather general review is given on current projects and recent achievements.

Introduction

Up until the end of the last decade, heavy ion research was the domain of only a few laboratories like Berkeley, GSI and Dubna. Then cyclotron facilities were starting to enter medium mass ion research, facilitated with the development of ECR sources. Also some tandem post accelerators provided high quality, high duty cycle beams around the Coulomb barrier.

By the mid 80's, the larger cyclotron facilities like GANIL and MSU could deliver beams of a hundred MeV/u for light ions and several tens of MeV/u for medium masses. The only facilities which could provide ions in the GeV/u range were converted weak focusing proton accelerators namely the Bevalac at Berkeley and the synchrophasotron at Dubna.

In contrast, the development of ion facilities since 1985 seems quite dramatic. If one looks for laboratories around the globe which have ion machines operating, under construction, or proposed, an impressive number is found. For cooler-storage rings the pace is even more impressive, with some ten projects to be realized in a short time span. Possibly there has never been such a density of individual major projects in the same field. Including some high energy centres which have recently entered the heavy ion business, more than 40 laboratories presently have ion beams available, or will have them soon.

Heavy ion physics today seems to be popular indeed. Research interests have also widened within the disciplines. The traditional fields of interest were nuclear structure and synthesis studies conducted with beam energies around the Coulomb barrier. With the advent of machines in the range of 100 MeV/u, research with exotic nuclei, reactions at the nuclear Fermi energy, and coherent nuclear effects like sub-threshold particle production were also investigated. Ion studies at the Bevalac up to 1 GeV/u were concentrated on nuclear equations of state and shock wave phenomena. Atomic physics with highly ionized particles was done too, but with only a small fraction of the primary effort.

Now, things are changing considerably. The new generation of accelerator-cooler-storage rings offers completely new possibilities for atomic physics and studies of beam cooling techniques. The investigation of interactions of partially and fully stripped ions with free electrons in the electron cooler sections or in separate electron targets allows a broad study of radiative electron capture (REC), dielectronic recombination (DR), and ionization processes. Due to the recirculation of the beam, the storage rings offer high currents and luminosity. The results of this research are of interest for both plasma and astrophysics. Besides the known stochastic and electron cooling, new techniques are planned like laser, dielectronic recombination and collisional cooling, as well as cooling with ultra cold electron beams. These techniques may also be applicable in existing facilities.

Another factor in the growth of new ion facilities has been the conversion of existing relativistic proton machines to very successful ion accelerators. In the last few years this has initiated a world wide effort in ultra relativistic ion physics experiments. The search for phase transitions and hope for the discovery of very hot dense matter containing quark gluon plasma in relativistic heavy ion collisions, have excited experimentalists. In addition there is a good chance that within the next three years, the jump can be made from light to very heavy ultra relativistic ions. Results from the first generation of light ion experiments at Brookhaven and at CERN look very promising.

In addition to these highlights, there is still interesting progress in the low and medium energy range. Part of this progress is due to the development of the ECR sources, which have set new standards for ion injectors. This source type now seems set to replace the penning ion source generation.

The intent of this paper is as a general review of the above developments that have taken place in the last two to three years. As separate papers on superconducting cyclotrons and on electrostatic accelerator facilities are presented at this conference, they will be excluded here. Nevertheless the remaining number of developing facilities and facilities under construction is so large that only brief descriptions are possible, with a few exceptions, which the author considered especially interesting.

Low Energy Accelerators and Storage Rings

Low Energy Linacs

In the low energy range (5 - 20 MeV/u) only the SuperHilac and the Unilac could provide beams in the full range of ions up to uranium. The next generation of machines under way of construction use next generation linac technology which can provide cw operation and presumably better beam quality. These are the ATLAS upgrade project at Argonne and the ALPI project in Legnaro (Italy). Both are based on superconducting rf-technology and on ECR ion sources. ATLAS is a superconducting linac with some 40 rf resonators, using a tandem as injector. The upgrade consists of a replacement of the tandem injector by an ECR ion source on a dc platform and a superconducting linac injector. In this new injector linac, quarter wave resonators are used for low velocity acceleration. The first set of these devices will become operational this year. This will allow the acceleration of ions up to xenon. With the completion of the final stage of the project at the end of 1990, the acceleration of uranium up to 5 MeV/u will be possible. Special care is taken to preserve the beam quality of the previous tandem injector operation by a carefully designed buncher-chopper system between the source and the injector linac. There is also taken care of the fact, that the high charge states from the ECR source type may complicate mass separation after the source. Intensities should be 100 times higher in the future.

ALPI is a linac project that recently received funding at Legnaro (Italy). It is a two stage project, which will start with 48 quarter wave superconducting rf resonators using the existing tandem as an injector. This will allow the acceleration of masses up to 130 above 6 MeV/u (1990). The second step, to be completed in early 1993, foresees the installation of additional 45 resonators. Uranium beams will then be possible up to 6 MeV/u, or with the planned ECR injector, to 10 MeV/u.

Low Energy Storage Rings

There are several cooler-storage rings with a maximum magnetic rigidity of around 2 Tm:
ASTRID is under construction in Aarhus (Denmark) with a circumference of 40 m with electron (3 keV) and laser cooling planned. This ring is to be used also as an electron storage ring. Commissioning is scheduled for 1989. The CRYRING project in Stockholm should be finished in 1990. This storage 45 m ring with a maximum magnetic rigidity of 1.4 Tm uses an electron beam ion source (EBIS) with an RFQ booster as injector. The electron cooler is designed for 20 keV.

The HISTRAP ring proposed at Oak Ridge has a 47 m circumference and is designed for 2.7 Tm. The commissioning phase has already started at the Heidelberg test storage ring TSR, which will be described in more detail below.

The typical ingredients of all these rings are straight sections for an rf-system, an electron cooler, and internal target stations. The rf-systems are used for acceleration or deceleration, rf-stacking, and bunching. The electron cooler is for reducing the longitudinal and transverse phase space of the beam, but it can also be used as an electron target for the different kinds of interactions between ions and free electrons. In addition, cooling via dielectronic recombination can be considered there.

On experiment sections, internal target of fibers, jets, electrons, and ions are planned as well as ion photon interaction. The latter implies the possibility of laser cooling of certain ion species. Stochastic cooling is planned for some of the rings, however, mainly in the medium energy storage rings to be treated below.

The electron cooling foreseen for all these rings, has some features which seem to be very attractive. Electron cooling is in principle independent of particle intensity. Thus one can achieve high brightness, high intensity beams. Electron cooling can be used within a wide energy range, continuously variable from ~ 5 to 500 MeV/u. That means that it is very flexible from the experimental point of view. In addition, one can also approach the different coherent and incoherent instability limits in the ring in the whole energy range. Also the Z^2/A-dependence of the cooling time is in favor of heavy ions, however, the cross sections for loss processes like radiative electron capture increase with the charge states, too. Intra beam scattering in particular is proportional to Z^4/A^2.

Proposals have been made to investigate ordering effects in very low temperature ion beams. This should be achieved by using specially designed ultra cold electron beam e.g. by using a GaAs photocathode. With this technique electron temperatures down to the K-range and accordingly low ion beam temperatures are predicted. In this case the coulomb energy between neighbouring ions would become large compared to the thermal energy kT (T ion beam temperature) so that ordering effects may set in. The ion beam could then assume a string, zig-zag chain or helix like structure.

At present, the Heidelberg test storage ring, TSR, is undergoing commissioning. It is a large acceptance ($A_{x,y}$ ~ 120 π mm mrad), 55 m ring with 1.5 Tm maximum rigidity. The first injection tests from a 15 MV Tandem with an rf-post-accelerator were performed in December, 1987. In April, 1988, the first 360° turn was reported, and by the beginning of June, the 10 turn injection of a 73 MeV carbon 6+ beam was achieved, with adiabatic rf capture and a 1 min beam lifetime.

There exist an impressive list of first phase experiments like laser and electron cooling (which will be available in late summer), a polarized hydrogen target, and the investigation of different recombination processes. The next two years will show how these new fields can develop in practice.

Low Energy Cyclotron Facilities

The energy range from 5 to about 150 MeV/u is the domain of superconducting and separated sector cyclotrons. As their energy is proportional to $(q/A)^2$ there is usually a steep decline in energy towards heavy ions. The acceleration techniques are well established, but the development of the ECR sources has brought significant gains in the energy and the range of ion masses which can be accelerated above the Coulomb barrier.

There are two new accelerators in this range which will be briefly presented here. The first is the RIKEN ring cyclotron, in Saitama, Japan, and the second the HIRFL (Heavy Ion Research Facility) at Lanzhou, China.
The RIKEN Cyclotron is a four sector K = 540 machine, which had its first beam extraction in December, 1986. Experiments have been running since summer last year with carbon to copper beams in the 20 to 42 MeV/u range. Ions up to lead are on the program. The present energy limitation is due to the injector linac (the only existing frequency variable Wideröe linac). In April next year a new K = 70 injector cyclotron should allow beams of 210 MeV for protons and 130 MeV/u for ions with q/A = 1/2.

The HIRFL is a K = 450 four sector cyclotron with injection from an existing K = 70 machine. Tests of the injection system started at the beginning of May, 1988. Extraction of an accelerated beam is scheduled for the end of this year. It is planned to accelerate ions from C to Xe. Both accelerators will enter next year the community of powerful facilities where nuclear research can be done from the Coulomb barrier up to the range of reaction mechanisms at the Fermi energy, of subthreshold π production, as well as the production and spectroscopy of exotic nuclei.

But existing facilities don't rest on their success. GANIL for instance, the largest European cyclotron facility is presently preparing an upgrade of its accelerator combination. It consists essentially of an optimization of the K = 380 cyclotron tandem, and the injector cyclotron for the higher charge states which can be produced by ECR sources. Presently the energy after the first cyclotron is large enough to strip ions fully up to argon, but is not sufficient for heavier ions. By modifying the injector cyclotron and the injection of the second sector cyclotron, higher initial charge states can be exploited so that the energy for medium and heavy masses is increased by up to a factor of two. Uranium can then be accelerated up to 20 MeV/u. The modifications will be installed in the first half of 1989.

Medium Energy Accelerators and Storage Rings

Medium Energy Storage Rings

There are five new cooler storage ring projects in the medium energy range which will become operational within four years. Most of these rings are dedicated to light ions, with only one designed for heavy ions. Accordingly, the physics attitude is different to that for the low energy storage rings. Atomic physics experiments are of less interest, but high quality nuclear and particle physics experiments with internal and external targets are planned for all. Magnetic rigidities range from 3.6 to 12 Tm and sizes range 78 m circumference to 180 m.

After the fundamental studies of electron cooling at CERN, Fermilab, and especially at the NAP ring in Novosibirsk, a new age dawned at November, 1987. At that time the electron cooler of LEAR was tested successfully in its first run. It was the first time that a ring used for experiments utilized electron cooling. The experiments were performed at proton energies of 49 and 21 MeV with 10^8 to 10^9 particles in the ring. This straight forward commissioning at LEAR was very encouraging for all members of the "Cooler-Club", who were eagerly watching, during their own design and construction work, the LEAR cooler device. As light ions are now available at CERN, there could eventually be another "first".

The TARN II ring in Tokyo has a circumference of 78 m and a magnetic rigidity of 7.3 Tm. The electron cooler is designed for 120 keV. In these respects it is similar to LEAR, but the lattices are different. This accelerator-cooler ring was primarily intended for the study of accelerator techniques like stacking and cooling. Now, internal target experiments and low intensity external beams are also considered with protons and ions up the neon. It is planned to put the facility into operation in 1989.

The CELSIUS ring in Uppsala is a 82 m machine for 7 Tm with a 300 keV electron cooler device. It is built up with dipole magnets previously used for the CERN initial cooling experiment, ICE. Beams of masses from 1 to 100 will be injected from an existing K = 200 synchrocyclotron. For experiments, which should start in 1989, different kinds of internal target are foreseen in order to study subthreshold π and near threshold hyperon production, as well as rare π^0 decays. The cooler storage ring of the IUCF in Bloomington successfully started commissioning this spring. The 87 m ring is specially designed to maximize the space available for straight experiment sections. There is no beam extraction foreseen. The magnetic rigidity is 3.6 Tm, which corresponds to a K of 600 in cyclotron terminology. In February, 1988, protons were accelerated in the ring for the first time. The acceleration time was about 1.7 s. The first electron cooling was achieved in March. The cooling time was about one tenth of a second for longitudinal cooling, thereby reducing the energy spread by a factor of twenty from 0.06 % to 0.003 %. The beam life time in the ring was 3 min with cooling and only 20 s without cooling. The transverse cooling time is estimated as 1 s, however, at the time being there are no appropriate diagnostics available. In April measurements were performed with the internal gas target, and cooling, as well as experiments with cooling including rf cavity operation. The combined action of cooling and rf resulted in 2 ns bunches within about 1 s for a 45 MeV proton beam. This configuration seems to be a very attractive option both for internal and external experiments at these cooler storage rings.

A characteristic feature of the COSY accelerator storage ring in Jülich is its long straight sections with telescope optics for the in-ring experiments, and the electron cooling apparatus. Electron cooling is planned to be used only at the injection energy and is correspondingly designed for 40 MeV protons. The stochastic cooling device will work at about 800 MeV/u. COSY is, with 180 m (12 Tm), by far the largest medium energy storage ring. Injection of p to Ar beams will be done from the JULIC cyclotron. There are equivalent experimental programs, mainly in the field of meson physics, for internal and external targets, to be started at the end of 1992.

At GSI Darmstadt an extension of the existing heavy ion accelerator facility is under construction. It consists of a heavy ion synchrotron, SIS (circumference 220 m), and an experimental storage ring, ESR (110 m). The Unilac, with some modifications, will be used as injector. Although this facility includes a synchrotron it is treated in this chapter because the combination with the storage ring provides unique features, which will be described below. The SIS is a 18 Tm synchrotron which can accelerate all elements up to uranium above 1 GeV/u. For light ions i.e. for q/A = 1/2 2 GeV/u can be reached. The planned intensities per pulse range from 10^{10} for uranium, to $5 \cdot 10^{11}$ for neon. The repetition frequency should be up to 3 Hz. The 10 Tm ESR is a large acceptance ring with $A_x > 300 \cdot 10^{-6}$ m and $A_y = 140 \cdot 10^{-6}$ m and $\delta p/p = \pm 2$ %. It will be equipped with a stochastic cooling device as well as an electron cooler with a range from 3 to 310 keV.

It is the combination of both accelerators which makes this facility unique in several respects. The SIS can provide beams for several purposes: (i) beams for a fixed target experimental area, (ii) beams of partially or fully stripped ions of all elements for atomic physics or internal target nuclear physics experiments, to the ESR and (iii) beams of selected radioactive nuclei. The latter is composed of target fragmented projectiles, which are selected in a specially designed fragment separator installed between the SIS and the ESR. In the ESR these "hot" beams can be stochastically precooled before electron cooling converts them, to high brightness beams with a low energy spread for in-ring or external experiments. For both purposes, stretcher and bunching modes (rf plus cooling) are possible. Beams prepared in the ESR can also be reinjected into the SIS for further acceleration. That would bring up the energy for uranium to 1.3 GeV/u when fully stripped. In the field of atomic physics, from light ions up to uranium, spectroscopy and ion-electron interactions can be studied on few electron or fully stripped ions. The maximum energy available and the excellent beam quality after cooling should allow the study of collective nuclear phenomena like subthreshold particle production from pions up to antiprotons.

Preparation of the site started at the end of 1986. Installation of the 24 SIS dipole magnets including the vacuum chambers is complete now with part of the quadrupole sections in place, as well. A full power test for all dipoles is scheduled for July, 1988. Tests of the SIS injection system should start in autumn this year. The construction of half of the magnets for the ESR is complete. Some of the other ESR components were manufactured together with SIS components. The commissioning of the ESR will start at the end of 1989, one year after SIS.

Medium Energy Accelerators

In the medium energy range (up to a few GeV/u) there are three accelerators now in operation: the Saturne (Saclay), the Bevalac (Berkeley), and the Synchrophasotron (Dubna).

Saturne has made a big step toward higher intensities and heavier ions by the successful commissioning of the MIMAS booster/accumulator ring. Previously, light ions from an EBIS/RFQ combination were preaccelerated in a linac. Since October, 1987, MIMAS accumulates and accelerates beams from the RFQ (187 keV/u) to 11.9 MeV/u with a charge to mass ratio of $q/A = 1/2$ for injection in Saturne. Argon beams have been used for experiments. Krypton and xenon beams up to 400 MeV/u are now possible.

The Bevalac is presently the only facility which can accelerate all elements up to uranium. An upgrade program is proposed there which essentially consists of a replacement of the old weak focusing Bevatron by a compact strong focusing synchrotron. This new ring should be installed inside the existing shielding of the Bevatron. This limits the circumference of the 17 Tm synchrotron to only 136 m.

High Energy Accelerators

At CERN in 1986 an oxygen beam was accelerated for the first time to 60 and 200 GeV/u in the CERN synchrotron complex. The beam started from the so-called oxygen injector at linac 1. It was built by a CERN-GSI-LBL collaboration. The key element was a 10 GHz ECR source from R. Geller, Grenoble, which delivered 80 to 120 μA O^{6+} ions. These ions were stripped to O^{8+} after the linac at 12 MeV/u and then accelerated to 260 MeV/u, 10 GeV/u, and 200 GeV/u in the PS-booster, the PS, and the SPS respectively. Intensities of some $4 \cdot 10^8$ particles per SPS pulse were achieved. These intensities were sufficient for the experiments, but were unusually low for the synchrotrons. Therefore some developmental effort was needed in the PS-booster control and beam diagnostic system, too, in order to make this run possible. At the PS a similar development was made for antiproton operation before. In 1987 the oxygen source was replaced by a 15 GHz source designed for S^{12+}. With this new source, sulfur ions were accelerated to 200 GeV/u in autumn 1987. The total kinetic energy of 6.4 TeV meant a world record. For the sulfur acceleration, a special operation mode was choosen where S^{12+} was only a ~ 5 % contamination of the O^{6+} beam from the ion source. In this way enough current was provided for the low velocity operation of the PSB. Both ions have a charge to mass ratio which differs only by $6 \cdot 10^{-4}$, also after stripping. They were not distinguishable by the RFQ, the linac and the PS-booster. The PS, however, is an extremely fine spectrometer at transition energy. There the S ions were driven inward, and the oxygen was driven outward. By using proper rf-programs at transition, either the oxygen, for setting up the SPS, or the sulfur was selected. Using oxygen, in this sense as a carrier beam, some $4 \cdot 10^7$ particles per SPS pulse could be delivered for sulfur.

These first experiments showed that in central nuclear collisions of ultra relativistic oxygen and sulfur ions with heavy target nuclei, large transverse momenta can be observed. That indicates strong nuclear stopping, and accordingly hot nuclear matter. So that quark gluon plasma seems to be within reach. But this is probably not the end of ion acceleration developments at CERN. Presently a proposal for a so-called "Lead Injector" is being prepared. The injector will consist of a new 18-20 GHz ECR source for Pb^{25+} (30-50 μA) and a new 4.5 MeV/u linac for the lower charge to mass ratio, replacing the linac 1. Necessarily, it also includes some vacuum improvements in the PSB and PS rings, as partially stripped ions are accelerated there. Provided that this projects gets the required funding of 30 Msfr, it could be completed in 1991.

Similar evolutions have proceeded at Brookhaven in the last few years, oxygen and silicon beams were accelerated in 1987 in the AGS to 14.5 GeV/u. Beams are injected into the AGS via a 700 m beam line from the tandem facility by multiturn injection (250 μs). A special rf-cavity boosts the heavy ions from 7 to 200 MeV/u, where the standard proton rf-system takes over. For oxygen and silicon, $5 \cdot 10^8$ and $1 \cdot 10^8$ particles respectively can be delivered per AGS pulse. The present injector/ring combination can accelerate ions up to mass 32 (sulfur).

The next step towards heavier ions has already commenced. In 1987, construction work for a 17 Tm, 210 m circumference booster for the AGS began. This will improve the AGS performance for proton and polarised proton operation, and also allow acceleration of ions up to gold 33+ to 350 MeV/u. Operation is scheduled for 1991. But that is not all from Brookhaven. A giant next step in the field of heavy ion acceleration has been proposed, namely the relativistic superconduction heavy ion collider RHIC, a 100 plus 100 GeV/u collider facility. For this collider one could use the existing 3.8 km ring tunnel from the abandoned CBA project, the CBA refriguration plant, and the partially equipped transfer tunnel from the AGS. The remaining cost is about 250 M$. The project could be finished within 5 years.

Conclusions

Low energy ion accelerators are now available worldwide, ranging in energy from the Coulomb barrier up to 100 MeV/u. In the near future several low energy cooler rings will offer completely new experimental fields in atomic physics research. High beam quality nuclear physics will also profit, especially by the medium energy cooler storage rings. The justification for building so many similar facilities at the same time may be better discussed in about 2 to 3 years. The most impressive achievement in the last 2 years is probably the enormous extension of energies in the ultra relativistic range, especially as is was done with so modest effort on the accelerator side.

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