REVIEW OF HIGH-POWER CYCLOTRONS FOR HEAVY-ION BEAMS

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Abstract

Since the development of heavy ion cyclotrons in the 1980s for use in the field of radioactive beam physics considerable effort has been made to upgrade these cyclotrons in terms of beam intensity and beam energy. This paper presents an overview of cyclotrons that provide heavy-ion beams with powers in the range of several hundred W and above. Some technological issues related to high-power heavy-ion beams are also discussed on the basis of the experiences of those cyclotrons.

INTRODUCTION

Several cyclotrons producing a wide range of heavy-ion beams were developed in 1980s to meet the increasing demand for heavy-ion beams [1]. They were designed to accelerate ions typically in the range of Q/A=1/2-1/3 at 50-100 MeV/nucleon and very heavy ions like uranium at 10-15 MeV/nucleon. Two types of cyclotrons were developed for this purpose: superconducting AVF cyclotrons and separated-sector cyclotrons (ring cyclotrons). The advent of ECR ion sources dramatically improved the performance of these cyclotrons [2,3]. These sources replaced the PIG-type ion sources that were originally used for the production of heavy ions. The use of ECR ion sources resulted in beams with higher intensities. Furthermore, the requirements for radioactive ion (RI) beam have promoted us to obtain much higher intensities as well as higher energies.

At present, several facilities worldwide operate cyclotrons with beam powers of approximately equal or greater than 1 kW. This paper describes the general features and status of six facilities that operate such cyclotrons along with some technological issues related to high-power heavy-ion beams.

HIGH POWER CYCLOTRONS NOW OPERATING FOR HEAVY ION BEAMS

In this section, the general feature and status of six facilities worldwide that operate high-power heavy-ion cyclotrons, along with their upgrade history, are described.

Table 1 lists the key parameters of the main cyclotrons at these facilities, and Figure 1 shows the statistics of beam power for the heavy ion beams produced.

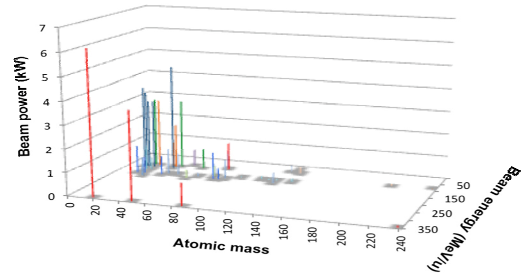

Figure 1: Statistics for the beam power of heavy ion beams obtained from high power cyclotrons so far.

GANIL

The Grand Accelerateur National d'Ion Louds (GANIL) in France is a heavy-ion accelerator facility that accommodates an accelerator complex consisting of three cyclotrons in series: a compact cyclotron (C01 or C02, K=30 MeV) and two separated-sector cyclotrons (CSS1 and CSS2, K=380 MeV) [4-7]. The first beam from the CSS2 was extracted in 1982. The number of sector magnets of the CSS2 is 4, and its maximum sector field, extraction radius and total magnet weight are 1.6 T, 3.0 m and 1,700 t, respectively. The facility delivers a wide spectrum of high intensity ion beams ranging from C to U at energies up to 95 MeV/nucleon.

The GANIL accelerator complex was originally designed taking into consideration the characteristics of PIG ion sources. However, several years later after its commissioning, it was redesigned and modified in order to meet the demands for very heavy ions with higher energies (OAE project) [8]. With these modifications, the output energies of the CSS2 for very heavy ions were increased by a factor of approximately two from 10 MeV/nucelon.

RI beams are obtained using two complementary methods: the projectile fragmentation method and the ISOL method. The RIs produced by the ISOL method are post-accelerated with a K265 compact cyclotron (CIME) at energies from 1.2 MeV/nucleon to 25 MeV/nucleon (SPIRAL1)[9,10]. The first beam from the CIME cyclotron was obtained in 1998. Upgrade in terms of beam intensity for the SPIRAL1 facility was performed [11-13].

Table 1: Key parameters of the six high power cyclotrons for heavy ion beams.

Facility	Main cyclotron	K-value (MeV)	Type	Main coil	No. of sectors	R_{ext} (m)	B_{max} (T)	Magnet weight(t)
RIBF	SRC	2,600	SS	SC	6	5.36	3.8	8,100
NSCL	K1200	1,200	AVF	SC	3	1.01	6.1	260
KVI	AGOR	600	AVF	SC	3	0.89	5.1	390
FLNR	U400M	550	AVF	RT	4	1.6	2.6	2,300
HIRFL	SSC	450	SS	RT	4	3.21	1.6	2,000
GANIL	CSS2	380	SS	RT	4	3.0	1.6	1,700

(SS: separated-sector, SC: superconducting, RT: room-temperature)

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At present, more than 10 primary beams with powers exceeding 1 kW are available; 3-5 kW beams of C, N, O, Mg and Ar ions and 1-2 kW beams of S and Kr ions are available for experiments [6,7,14].

NSCL/MSU

Two superconducting AVF cyclotrons, K500 and K1200, are operated at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University (MSU), U.S.A. [15-21]. This facility can deliver a wide range of primary beams from hydrogen to uranium at energies up to 200 MeV/nucleon. Various kinds of RI beams, which are produced via the projectile fragment method using the superconducting fragment separator A1900, are used for experiments.

The K500 cyclotron (K=500 MeV) is the first superconducting cyclotron, and the K1200 (K=1,200 MeV) is the largest superconducting AVF cyclotron. The first beams from the K500 and K1200 cyclotrons were obtained in 1982 and 1988, respectively. The number of sectors of the K1200 is 3, and its maximum magnetic field, extraction radius and total magnet weight are 6.1 T, 1.01 m and 260 t, respectively. A superconducting ECR ion source SuSI recently became operational.

The K1200 cyclotron was operated in the stand-alone mode (direct injection of beam from the ECR ion source into the K1200) at the beginning by using the highly charged ions then available from the ECR ion source, although the original proposal was to use the K500 with an internal PIG ion source as an injector [18]. Then, the Coupled Cyclotron Facility (CCF) project was started in the early 1990s with the objective of increasing the beam intensity by coupling the K500 and K1200 [19,20,22]. Ion beams extracted from the K500 are transported and injected into the K1200 by stripping using a carbon foil located near its center. The beam energies for very heavy ions can be increased with this scheme, although those for light heavy ions are maintained at 200 MeV/nucleon. In this project, the K500 cyclotron was refurbished and a new beam injection system was installed in the K1200 cyclotron accordingly. The first beam from the coupled cyclotrons was obtained in 2000.

A continuing program of beam development in the low energy beam transport (LEBT) has been performed [23]. At present, beams of O, Ne, Mg, Ar, ^{48}Ca, Kr ions, etc. are available at energies from 120 to 170 MeV/nucleon with a beam power of approximately 1 kW [24].

FLNR/JINR

Four isochronous cyclotrons are operated at the Flerov Laboratory of Nuclear Reactions (FLNR) at the Joint Institute for Nuclear Research (JINR) in Russia: U400, U400M, U200 and IC100 cyclotrons [25-30]. The U400 and U400M cyclotrons are used for the acceleration of high-power heavy-ion beams (DRIBs project). The first beams from the U400 (K=625 MeV) and U400M (K=550 MeV) cyclotrons were obtained in 1978 and 1991, respectively. The number of sectors of the U400M cyclotron is 4, and its maximum magnetic field, extraction radius and the total magnet weight are 2.6 T, 1.6 m and 2,300 t, respectively. The internal PIG ion sources in the U400 and U400M cyclotrons were replaced by ECR ion sources in the mid 1990s. Beams are extracted from both the cyclotrons using a thin stripping foil with an efficiency of approximately 40 %, for example for ^{48}Ca beams.

About 66 % of the total operation time is used for the acceleration of ^{48}Ca ions to synthesize new superheavy elements. Another characteristics of this facility is that RI beams produced by the ISOL method using primary beams extracted from the U400M are transported along a 120-m transfer line and post-accelerated by the U400.

At present, various kinds of ions, O, Ar, ^{48}C, Ti, Fe, Kr, Xe, etc. are obtained from the U400M. The energies of these beams range from several to about 15 MeV/nucleon, among which the beam power of oxygen ions exceeds 1 kW and the beam intensity of ^{48}Ca ions is 1.2 pμA. An upgrade project for upgrading from U400 to U400R, and increasing beam intensities up to 2.5-3 pμA, and increasing the available energy variation by a factor of 5 for ^{48}Ca, ^{50}Ti, ^{54}Cr, ^{58}Fe and ^{64}Ni ions is planned to start in 2010 and end in 2011.

HIRFL

The Heavy Ion Research Facility in Lanzhou (HIRFL) in China, consists of an injector AVF cyclotron (SFC, K=69 MeV), a separated-sector cyclotron (SSC, K=450 MeV) and two newly constructed electron cooler synchrotrons, CSRm and CSRe [31-34]. The first beam from the SSC was obtained in 1988. The number of separated sector magnets of the SSC is 4, and its maximum sector field, extraction radius and total magnet weight are 1.6 T, 3.21 m and 2,000 t, respectively. The commissioning of the CSRm started before the end of 2005 and a $^{12}C^{4+}$ beam at 7 MeV/nucleon from the SFC was injected and accumulated in the CSRm for the first time in 2006.

In the beginning of 2000s, a series of upgrades were performed: the replacement of the vacuum chamber of the SFC, installation of a new rebuncher between the SFC and the SSC, increasing the RF voltage for both the SFC and the SSC, improvement of the control and diagnostic systems, and replacement of all the power supplies in the facility. A dramatic enhancement of the HIRFL performance was achieved by this upgrade. The use of the superconducting ECR ion source SECRAL, which has been operational since 2005, further increased the HIRFL performance [35].

At present, various kinds of ions up to Bi are available from the SSC at energies from 10 to 100 MeV/nucleon. The available beam power is generally low except for $^{36}Ar^{18+}$ beam at 22 MeV/nucleon (350 W), which is used for the injection into the CSRm, since the beam transmission mainly through the SSC is still somehow poor. On the other hand, the beam power from the SFC is the highest among such cyclotrons, as high as 100-300 W for O-Xe ions with beam energies of several MeV/nucleon [36]. This implies that the beam power from the SSC can be easily increased above 1 kW by improving the beam transmission through the SSC.

KVI

A superconducting isochronous cyclotron called AGOR is operated at the Kernfysisch Versneller Instituut (KVI) at University of Groningen, the Netherland [37-40]. The AGOR cyclotron (K=600 MeV) was designed and constructed through the collaboration between l'Institut de Physique Nucleaire (IPN), Orsay and KVI, Groningen, and the first beam at KVI was obtained in 1996. The number of sectors of the AGOR cyclotron is 3, and its maximum magnetic field, extraction radius and total magnet weight are 5.1 T, 0.89 m and 390 t, respectively. The facility delivers heavy-ion beams at energies from several to 90 MeV/nucleon as well as protons up to 190 MeV.

In the early stages of operation, the AGOR cyclotron suffered internal beam losses due to the large coherent vertical motion of the proton beam with the highest energy; this was not observed in the case of heavy-ion beams [41]. The reason for this problem was determined by the careful measurement of the vertical beam position as a function of radius and a detailed study of the beam dynamics. The internal beam losses disappeared by the shifting of the main coil position by -0.34 mm.

A beam power of 1 kW has been achieved so far for Ne ion beams of 23 MeV/nucleon. An upgrade project for increasing the beam intensity in order to obtain a beam power of ~1 kW for all beams up to Bi is underway. The upgrade includes the construction of a new ECR ion source, improvement of the LEBT system, reconstruction of a part of the extraction system, and development of a beam loss monitoring and control system.

RIBF

The RI Beam Factory (RIBF) at RIKEN Nishina Center, Japan, is a heavy-ion accelerator complex consisting of two different types of injectors – a unique variable-frequency heavy-ion linac (RILAC) and an AVF cyclotron (K=78 MeV) – and four ring cyclotrons, the RRC, fRC, IRC and SRC with K-values of 540, 570, 980 and 2,600 MeV, respectively, from the upstream [42-47]. The facility can deliver a variety of ion beams from hydrogen to uranium at a wide range of energies from several to several hundreds MeV/nucleon.

The RILAC, AVF cyclotron and RRC are used in the old facility that is in operation since 1986 when the first beam from the RRC, injected from the RILAC, was obtained. The maximum energy of ion beams from the RRC is 135 MeV/nucleon for ions such as C, N, O and around 15 MeV/nucleon for very heavy ions. A projectile fragment separator, RIPS [48], in combination with these accelerators produces the intense RI beams with atomic masses of around 50 or less.

The RIBF project was started in the mid 1990s with the aim of increasing beam energies in order to meet the strong demands from users for different kinds of RI beams up to uranium. First, the pre-injector of the RILAC was upgraded in an attempt to increase the beam intensities of very heavy ions. The pre-injector system consisting of an 8 GHz NEOMAFIOS and a 450-kV Cockcroft-Walton terminal was replaced with a new system consisting of an 18 GHz ECR ion source and a variable-frequency FC-RFQ linac [49,50]. The construction of new cyclotrons for the RIBF project then started in late 1990's. The construction of three new ring cyclotrons, fRC, IRC and SRC was completed in 2006, and the first beam from the SRC was obtained at the end of 2006.

The SRC is the world's first and world's most powerful superconducting ring cyclotron [51]. The number of the separated sector magnets of the SRC is 6, and its maximum sector field, extraction radius and total magnet weight are 6, 3.8 T, 5.36 m and 8,100 t, respectively. The RIBF accelerator complex provides various modes of acceleration. The maximum energy of the beams from the SRC thus obtained is 440 MeV/nucleon for ions with Q/A=1/2 and 345 MeV/nucleon for all kinds of ions up to uranium. The target beam intensity is set to be 1 pμA, which is limited by the radiation shielding power around the primary beam dump. Radioactive ion beams are produced using a superconducting fragment separator, BigRIPS [52], via two methods: the projectile fragmentation of stable heavy ions or in-flight fission of uranium ions.

The SRC have so far delivered polarized deuterons and ^{14}N beams at 250 MeV/nucleon; α beams at 320 MeV/nucleon; and ^{18}O, ^{48}Ca, ^{86}Kr, ^{238}U beams at 345 MeV/nucleon. The beam intensities of the α and ^{18}O beams were 1 pμA, which is limited by the safety regulation rule. Their beam powers were 1.3 kW and 6.2 kW, respectively. The beam intensities of the ^{48}Ca and ^{238}U beams were 230 pnA and 0.8 pnA, respectively. Their beam intensities were limited by the beam loss at the electrostatic deflector of the SRC and the beam intensity of the ECR ion source, respectively. A search for new isotopes was carried out in 2008 by employing the in-flight fission of a 345 MeV/nucleon ^{238}U beam with an average beam intensity of 0.2 pnA, which is 5,000 times less than the target intensity, and 45 new neutron-rich isotopes were observed [53]. This result verified the potentiality of the RIBF.

A new injector linac, RILAC2, consisting of a 28 GHz superconducting ECR ion source, an LEBT system, an RFQ linac and three DTLs is under construction [54,55]. It will be ready for commissioning by the end of 2010. Uranium beam with intensities of 50-100 pnA are expected to be obtained from the SRC by the use of this new injector in the near future.

SOME TECHNOLOGICAL ISSUES RELATED TO HIGH-POWER HEAVY-ION BEAMS

This section discusses some technological issues concerning high-power heavy-ion beams, based on the experiences in operating the above-mentioned facilities.

ECR Ion Sources

One of the challenging tasks for ECR ion sources is to produce more than 500 eμA U^{35+} ions, which are necessary to attain the beam intensity of 1 pμA from the SRC at the RIBF. Fortunately, the performance of ECR ion sources has been remarkably increased with the development of 3rd generation superconducting ECR ion sources (SC-ECRISs) such as VENUS [56], which is the first among them, and SECRAL [35], which has a unique magnetic structure with all the axial solenoid coils located inside a superconducting sextupole magnet. The VENUS, for example, has already produced 175 eμA U^{35+} ions, which means that the value of 500 eμA is within arm's reach. A 28 GHz superconducting ECR ion source has recently been developed at the RIBF [57,58]. The main features of this ion source are as follows: (1) it has six solenoid coils for producing magnetic mirrors in the axial direction, and (2) the magnetic field gradient and ECR zone size can be changed independently using this configuration. Production tests using 18 GHz microwaves showed that a smaller field gradient and a larger size of the ECR zone gave a higher beam intensity as expected. Therefore, this ion source is expected to produce a U^{35+} beam with the intensity of more than 500 eμA.

LEBT

It is very important to control the quality of beams in the LEBT system from the ECR ion source to the injector. At NSCL, for example, an intensive study of the behavior of beams in the LEBT was carried out using BaF_2-coated viewing plates and an Allison-type emittance scanner [59]. The image of the beam on the viewing plate showed a hollow shape when a significant fraction of the unanalysed beam had a higher charge-to-mass ratio than the desired beam. By attributing this result to the effect of space charge forces from the unanalysed beam, a solenoid located between the ECR ion source and the analyzing magnet was replaced with an electrostatic lens. As a result, the net beam transmission efficiency was improved by 400 % over the period 2003-2006.

A more detailed study involving both simulations and experiments has to be carried out to further elucidate the mechanism of beam motion in the LEBT system. Neutralization and the initial condition at the extraction of the ion source etc. are important factors to be investigated.

Extraction

A key factor limiting cyclotron output beam intensity is beam loss at electrostatic deflectors. The problem is serious for heavy ion beams, which have high power density in the Bragg peak of them, leading to greater damage to the septum electrode. Therefore, the beam extraction should be carefully tuned. In the SRC at RIBF, for example, the temperature of the septum electrode and the radiation from it are constantly monitored using thermocouples attached to the electrode and loss monitors located in the neighbourhood of the deflector, respectively. Here, the temperature rise is kept below the value that corresponds to a beam loss of 300 W.

Some of the ways to reduce the beam loss at the deflector are increasing the RF voltage, using a flattop resonator and collimating the beam at the upstream [23]. In addition, a deflector that can endure higher values of beam loss, say 1,000 W, would also be necessary [60].

Charge Strippers

Another set of components that strongly limit output beam intensity, and thus availability (mentioned later), are the charge strippers used for very heavy ions. In the acceleration of a uranium beam at RIBF, two major problems occur with the first of the two carbon foil strippers – the 0.3 mg/cm2 foil at 11 MeV/nucleon (from U^{35+} to U^{71+}) and the 17 mg/cm2 foil at 51 MeV/nucleon (from U^{71+} to U^{86+}) - used after the RRC and the fRC, respectively. One is their finite lifetime and the other is the energy spread due to the non-uniformity in foil thickness [47]. In the experiment carried out in 2008 and 2009, the lifetimes were as short as 10-12 h with a beam intensity of 14 pnA and 10 h at the longest with a beam intensity of 80 pnA [61], respectively. Different kinds of carbon foils, including diamond-like carbon and multi-layer carbon [62], have been tested with no satisfactory results. The non-uniformity in foil thickness is approximately 30 %, as estimated by comparing the longitudinal widths of the beams generated with and without the carbon foil. Thus, a switch to 0.2 mg/cm2 carbon foils (to U^{69+}) is planned, together with minor modifications to the fRC power supplies, in order to mitigate the energy spread.

The target intensity for the uranium beam at RIBF is approximately 1,000 times higher than what is currently available. It is necessary, therefore, to develop charge strippers that can endure such high intensity uranium beams as soon as possible. For this purpose, one of the possibilities being investigated is that of using a gas stripper [63]. The use of a liquid-Li stripper foil [64] is another such possibility.

An experiment recently performed in the K1200 cyclotron at NSCL using a Pb ion beam showed that the beam transmission through the cyclotron decreased significantly at 10^{14} ions in the beam spot area of 4 mm^2 and that the carbon foil experienced significant changes after irradiation [65]. It was concluded that carbon foils are not practical to use for very heavy ions at the present time.

Beam Diagnostics/Safety System

Non-destructive beam diagnostic devices are indispensable for high-intensity operations. At GANIL, in the operation of high-power beams, the machine is tuned step by step by reducing the beam-chopping rate and monitoring the beam losses using two types of diagnostics [66]: interceptive diaphragms or copper plates located at the entrance and exit of dipole magnets as well as the entrance of the inflectors and deflectors inside the cyclotrons, and current transformers located in the beam lines. During the delivery of the beam to the experiment, the beam loss is continuously monitored and if it exceeds a threshold, the safety system quickly stops the beam with the chopper. At RIBF, a monitoring system of beam phases and RF fields using lock-in amplifiers (LIAs) has recently been developed [67]. The system constantly monitors fluctuations in the voltages and phases of 25 RF resonators in total, the output signals of 13 phase pickup probes placed along the beam transport lines and those of 69 phase pickup probes in total placed in the RRC, fRC, IRC and SRC. An automated beam alignment system using inductive beam position monitors (BPMs), such as the one adopted in iThemba LABS [68], is also useful.

Stability

One of the issues concerning cyclotrons is the instability of the magnetic fields due to the huge size of the magnets. The magnetic field strength of the RRC at RIBF drifts particularly fast, at a rate of approximately 1 ppm/h, for the first 600 h, whereas those of the IRC and SRC are stable. It is expected for this drift to be suppressed by the procedure similar to that adopted for the Takasaki AVF cyclotron [69,70]; that is, by controlling the temperature of the magnet iron, by thermally isolating the main coil from the yoke and by precisely controlling the cooling water temperature of the trim coils attached to the pole surfaces.

Availability/Reliability

Operational statistics at every facility show that the availability of the machine, defined as the ratio of the delivered beam time to the scheduled beam time, is now as high as 90 % [14,40,71]. In the operation of 345 MeV/nucleon ^{48}Ca beam carried out at RIBF in May and June, 2010, an availability of approximately 80 % was achieved, which was an improvement over the 60 % availability achieved in 2008 [55].

It is important to note that an electric power co-generation system (CGS) with the maximum output of 6.5 MW is operated at RIBF in order to increase the reliability and overall energy efficiency of the power supply to the entire facility [72,73]. Apparatus requiring non-stop operation, such as the He refrigerator for the superconducting sector magnets of the SRC, are powered by the CGS. When the CGS stops, the equipment is immediately switched over to the commercial power grid. The CGS also contributes to the increase in the availability of the facility.

Space Charge Effect

There has been little study until now on the space charge effects on heavy ions in cyclotrons, whereas considerable research has been devoted to space charge effects for high-intensity protons, for example, in the PSI cyclotrons [74,75]. However, it has become necessary to take these effects into account in simulations since the recent high power cyclotrons are required to accelerate high-intensity, highly charged heavy ions. In Ref. 76, the phenomenon of “round beam” formation, which was observed and has been studied [77] in the PSI proton cyclotron, Injector II, and its matching condition for heavy ion beams are discussed both analytically and numerically. Recently, a numerical simulation demonstrates that beams of U^{35+} ions with an intensity of 0.5 emA form a “round beam” in the RRC at RIBF [78]. Another simulation shows that the intensity limit due to the longitudinal space charge effects for the U^{88+} ion beam in the SRC at RIBF is approximately 2 pμA, which is twice the target intensity [79]. Further simulations are necessary to understand and control the behavior of high-intensity heavy ion beams.

SUMMARY

High power cyclotrons for heavy ion beams have played an essential role in RI beam sciences. In this paper, six such cyclotrons are reviewed by describing their general features and status. In addition, some of the technological issues related to them are discussed. High-power heavy-ion cyclotrons are expected to be more and more useful for RI beam sciences.

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