REVIEW OF HEAVY-ION CYCLOTRONS

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Abstract

The basic features of heavy-ion cyclotrons are briefly summarized and various activities concerning heavy-ion cyclotron facilities worldwide are reviewed with an emphasis on important achievements and recent upgrades.

INTRODUCTION

Livingston reported that the 37-inch Berkeley cyclotron first accelerated a carbon beam up to 50 MeV in 1940 [1]. Seventy-five years have passed, and dramatic augmentations of beam energy, intensity, and ion species have been obtained for heavy-ion cyclotrons. Bending indices (K_B) for heavy-ion cyclotrons commissioned after 1980 and those commissioned before 1980 but currently working are plotted in Fig. 1 by year of commissioning. The bending limit of cyclotron energy is given by $E/A = K_B \times (q/A)^2$, where E, q, and A are the total kinetic energy, charge state, and mass number, respectively. These data are based on the "List of Cyclotrons" compiled in 2005 [2] and include newly commissioned cyclotrons and recent developments reported at subsequent international cyclotron conferences.

Many heavy-ion cyclotrons were commissioned from 1980 to 2000. Two major trends are innovation in compact superconducting (SC) cyclotrons and the introduction of separate-sector (SS) cyclotrons for heavy ions. Conventional Thomas-type cyclotrons have also been continuously commissioned. Most of the cyclotrons shown in Fig. 1 have undergone upgrades since their commissioning. In this review, these heavy-ion cyclotrons are classified into three groups according to their type. Their basic features are briefly summarized and important achievements so far and recent (up to 2013 or 2014) upgrades are described. Note that some important activities such as those related to heavy-ion cyclotrons dedicated to medical uses, innovative design studies, and novel applications are not included in order to remain within the paper's space limitations and the author's area of expertise.

COMPACT CYCLOTRONS

More than 20 compact cyclotrons are currently in operation, some of which are listed in Table 1. All of them are Thomas-type cyclotrons [3]. The bending indices (K_B) of the compact cyclotrons shown in Fig. 1 range from 10 to 625 MeV, but cyclotrons with K_B of 100–200 MeV are widely used for stand-alone operations. The isochronous magnetic field is formed by a set of magnet poles with an azimuthally varying gap and a set of main and trim coils. Conventional dee electrodes are used for acceleration with typical voltages ranging from 50 to 100 kV. These cyclotrons are now equipped with electron cyclotron resonance (ECR) ion sources and beams are axially injected. Beam extraction is performed by the electrostatic deflector (ESD) or charge-stripping technique.

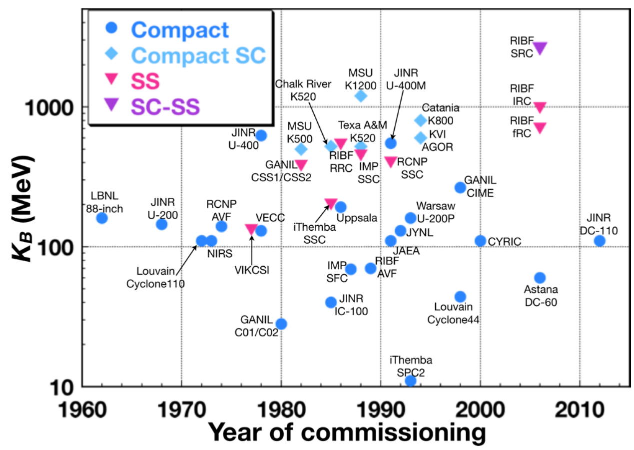

Figure 1: Heavy-ion cyclotrons.

University of Jyväskylä (JYFL)

The main accelerator at JYFL is the K130 cyclotron [4] constructed by Scanditronix. Since its commissioning in 1992, the cyclotron has been used for both nuclear physics and applications. The latter includes testing space electronics and producing medical isotopes and nano-filters. The annual use of K130 has exceeded 6000 h for more than 15 years [5]. To meet increasing demands, a new compact cyclotron (MCC30/15) producing high-intensity 30-MeV H^- and 15-MeV D^- beams was introduced in 2009 [6], and the building facilities were expanded. JYFL has demonstrated that a medium-scale isochronous cyclotron combined with original and sophisticated experimental techniques can make important contributions to nuclear physics studies.

Lawrence Berkeley National Laboratory (LBNL)

The historically famous 88-inch cyclotron at LBNL commissioned in 1962 serves highly charged ions like Xe^{43+} for microchip testing and medium-charge-state high-intensity beams (^{48}Ca) for nuclear physics experiments [7] thanks to its powerful ECR ion sources, AECR-U and VENUS. Super-heavy element research demands higher-intensity ^{48}Ca beams, so the low-energy part of the facility was modified to reduce the space charge effect. Specifically, the extraction voltage of the AECR-U ion source was increased from 14 to 25 kV, which is comparable to that of VENUS. The axial injection line was also modified to manage 25-kV

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extraction. A new spiral inflector dedicated to high-intensity medium-heavy ions was also introduced [8]. As a result, a 250-MeV ^{48}Ca beam with a peak intensity of 2 pμA was obtained. The high-intensity ^{48}Ca beam was delivered to an 8-week-long experiment. The average intensity ranged from 1.1 to 1.5 pμA and the consumption rate of ^{48}Ca at the source was 0.27 mg/h on average.

FLNR JINR (Dubna)

FLNR has operated two big cyclotrons (U-400 and U-400M) for nuclear physics and two smaller cyclotrons (U-200 and IC-100) for application uses [9]. These cyclotrons are all of the four-sector type with two or four dee electrodes. The charge-stripping extraction technique is widely used [10]. U-400 was commissioned in 1978 and upgraded in 1996 [11]. The upgrade, aimed at stable operations with low material consumption at the source, replaced the old internal PIG source with an ECR ion source. An axial beam injection system was also introduced. U-400 has contributed greatly to super-heavy-element research [9] and its modernization to U-400R is ongoing [12]. U-400M is used to produce light exotic nuclei. In the Dubna Radioactive Isotope Beams (DRIBs) project, U-400 and U-400M are used as a driver and a post-accelerator. Furthermore, construction of a new cyclotron DC-280 has started to greatly enhance the present beam intensity of 250–270 MeV ^{48}Ca (1.4 pμA) [13]. 10-pμA ^{48}Ca beams are planned at DC-280 [14].

Industrial applications such as production of nuclear track membranes are also being actively pursued at FLNR. IC-100 (DC-40) was modernized in 2004, when an SC-ECRIS and an ESD were introduced [15]. In addition, a new cyclotron DC-110 dedicated to industrial applications was commissioned in 2012. It successfully produced beams exceeding 10 μA for 2.5*A*-MeV Ar, Kr, and Xe beams [16].

Post-accelerators

Acceleration of radioactive isotope (RI) beams requires a wide-energy-range, large-acceptance, high-mass-resolution machine. Suitably designed cyclotrons fulfill these requirements. A good example is CIME [17] at the GANIL-SPIRAL facility. CIME was designed to accelerate RIs up to adjustable final energies ranging from 1.7*A* MeV to 25*A* MeV. Two central-region geometries covered a wide RF harmonic ranging from 2 to 5. The harmonic range was later increased to 6 to obtain lower-energy beams. The acceptance was designed as 80π mm-mrad, a good vacuum (5×10^{-6} Pa) was achieved, and silicon and scintillation detectors were equipped to diagnose faint RI beams. As a result, many gaseous elements have been accelerated by CIME [18]. The mass resolution obtained was at the 10^{-4} level [19].

Cyclone 110 and Cyclone 44 at Université catholique de Louvain were also engaged in post-acceleration. The latter was dedicated to low-energy RI beams for astrophysical interests [20].

Table 1: Specifications of various compact heavy-ion cyclotrons. Compiled data [2] are used, but data noted as (1) and (2) are from individual reports [21] and [22], respectively.

Facility & machine	K_B (MeV)	No. of sectors	Spiral angle (deg.)	Gap hill/valley (cm)	No. of dees	V_{gap} (kV)	Frequency (MHz)	Beam extraction
Jyäskylä K130	130	3	58	17.4 / 33.0	2	50	10–21	ESD / CS
JAEA-Takasaki AVF	110	4	53	16.6 / 40.5	2	60	10.6–22	ESD
CYRIC K110	110	4	53	16.6 / 40.5	2	60	10.6–22	ESD / CS
LBNL 88-inch	160	3	55	19.0 / 30.0	1	50	5.5–16	ESD
Warsaw U-200P	160	4	0	2.6 / 15.0	2	70	12–18$^{(1)}$	CS
FLNR JINR U-400	625$^{(2)}$	4	0	4.2 / 30.0	2	100$^{(2)}$	5.5–12$^{(2)}$	CS
FLNR JINR U-400M	550$^{(2)}$	4	43$^{(2)}$	10.0 / 50.0	4	170$^{(2)}$	11.5–24$^{(2)}$	CS
VECC K130	130	3	~55	19.0 / 30.0	1	60	5.5–15.5	ESD
GANIL CIME	265	4	0	12.0 / 30.0	2	100	9.6–14.5	ESD
TSL Gustaf Werner	192	3	55	20.0 / 38.0	2	50	12.3–24.0	ESD

COMPACT SC CYCLOTRONS

Compact SC cyclotrons were pioneered by the Chalk River [23] and MSU [24] groups. The aim was to accelerate all the ion species from proton (or H_2^+) to uranium up to much higher energies than previously obtained with moderate construction costs. Table 2 summarizes the specifications of the compact SC cyclotrons already commissioned. Important features of these cyclotrons have been reviewed in detail by several experts, especially by Blosser et al. [25]. Some basic features are recalled here.

These compact SC cyclotrons adopt room-temperature (RT) magnet poles, liquid-helium-cooled SC main coils and RT trim coils or trim rods (Chalk River) for isochronous magnetic fields, conventional dee electrodes for acceleration, and ESDs for beam extraction. A set of iron poles produces azimuthally varying magnetic fields essential for vertical focusing of the ion's betatron motion. Iron poles are fully saturated on the whole operating diagram. An SC main coil is divided vertically into two individually excitable coils, namely, the inner (near the median plane) and outer coils. The inner and outer coils both produce azimuthally symmetric fields but their radial

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profiles differ. Excitation currents of the inner and outer coils are adjusted so as to obtain coarse isochronism for a wide variety of mass-to-charge ratios and beam energies to realize modest power consumption of the trim coils used for fine isochronism.

Betatron tunes of the ion in the cyclotron vary according to the ion's energy during acceleration. In addition, betatron tunes in the compact SC cyclotron depend strongly on the excitation level of the magnet, because the magnetic-field profile changes according to excitation currents in the SC main coils, which produce azimuthally symmetric magnetic fields, but with the flutter magnetic field of the iron poles unchanged. This behavior of tunes, together with tight resonance conditions especially imposed on three-sector machines, requires a delicate magnet design. For example, $\nu_r = 2\nu_z$ and $\nu_z = 1$ resonances are usually crossed in these cyclotrons. In addition, $\nu_r = 1$ resonance is also crossed just before beam extraction, by which a radial betatron oscillation is induced and the turn separation is widened for efficient beam extraction (precessional extraction). Another difficulty in beam extraction is variation of orbit geometry caused by variation of the magnetic-field profile.

Pioneering researchers finally solved these difficulties, providing many valuable lessons. These compact SC cyclotrons demonstrated their capabilities covering a wide working region [26–29]. MSU K1200 fully covered its operating diagram in its stand-alone operation mode [26]. KVI-AGOR accelerated not only heavy ions with energies ranging from 10*A* to 85*A* MeV, but also 190-MeV protons [27]. The maximum energy obtained by LNS-SC (K800) of INFN-LNS was limited due to insufficient deflector performance in 2001 [28], but later increased to 80*A* MeV [30].

Table 2: Basic parameters of compact superconducting cyclotrons. Compiled data in [2] are used except for Chalk River K520 [31] and VECC K500 [32].

Facility & machine	K_B (MeV)	K_F (MeV)	R_{ext} (m)	Gap hill/valley (cm)	No. of sectors and dees	B_0 (T)	Frequency (MHz)	Stored energy (MJ)
Chalk River K520	520	100	0.65	3.7 / 65.0	4	2.4–5.0	31–62	22
INFN-LNS LNS-SC	800	200	0.87	8.6 / 91.6	3	2.2–4.8	15–48	45
KVI AGOR	600	220	0.9	7.0 / 168	3	1.7–4.1	24–62	56
NSCL-MSU K500	500	160	0.66	6.35 / 91.4	3	3.0–5.0	11–27	18
NSCL-MSU K1200	1200	400	1.0	7.6 / 91.4	3	3.0–5.3	9–27	60
Texas A&M K500	520	160	0.67	6.35 / 91.4	3	3.1–4.9	9–28	16.9
VECC K500	520	160	0.67	6.35 / 91.4	3	3.1–4.9	9–27	22

High-intensity Operations

To meet increasing demands for rare isotope beams, these compact SC cyclotrons have upgraded their beam intensities. At INFN-LNS, construction of an ISOL-type facility started in 1995 (the EXCYT program). Its original acceleration scheme used the 15-MV Tandem as an injector and the K800 cyclotron as an energy booster. In the EXCYT program the K800, equipped with ECRISs and an axial injection system, serves as a driver and the 15-MV Tandem as a post-accelerator. For light ions, 1-pμA primary beams were envisaged [33]. A further intensity upgrade, aiming at 20-kW light ion beams using charge-stripping extraction, was also proposed at INFN-LNS [28]. NSCL at MSU proposed the Coupled Cyclotron Facility (CCF) using its two existing compact SC cyclotrons K500 and K1200 in order to realize a thousand-fold increase in the yield of rare isotope beams produced by its fragment separator. In the CCF, high-intensity beams extracted from ECRISs are axially injected into K500 and the extracted beams from K500 are injected radially into K1200 via charge stripping [34]. In 2003, KVI started its TRIμP program, in which violation of time-reversal symmetry was tested by RI beams. One-kilowatt beams were required for Ne and Pb [35].

To fulfill these requirements, high-performance ECR ion sources were introduced, new axial injection lines and central regions were constructed at INFN-LNS [36] and NSCL [37], the extraction systems were improved, beam loss was carefully controlled [35], and other measures were taken. As a result of these upgrades, the CCF now delivers high-energy (approx. 150*A* MeV) heavy-ion beams with beam powers exceeding 1 kW [38]. Almost 900 RI beams have been used in experiments there [39]. AGOR also achieved 1-kW light ion beams [40].

Texas A&M started a RI beam program based on the ion guide technique. Its old 88-inch cyclotron was re-commissioned as a driver cyclotron and K500 will be used as a post-accelerator [41]. VECC obtained its first internal beam at K500 in 2009 [42].

Separate-orbit Cyclotron Prototype (Tritron)

Trinks proposed an SC version of the separate-orbit cyclotron (SOC) [43]. The SC-SOC consists mainly of SC magnetic channels and SC acceleration cavities. The former define a spiral-shaped orbit along which ions are accelerated. The latter produce sufficient turn separations required by the geometry of SC magnetic channels. SC magnetic channels covering the same azimuthal region form a sector, in which channels are radially separated from each other and enclosed by a set of steel frames.

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Each SC channel produces a magnetic flux inside its small aperture, and the magnetic flux is immediately returned in the adjacent part of the steel frames. Voluminous return yoke is not necessary. Each SC channel has essentially no effect on neighboring turns and transverse and longitudinal focusing properties can be designed more freely than in conventional cyclotrons. AG focusing in the transverse directions and phase stability in the longitudinal direction are available. Trinks and collaborators constructed a prototype SC-SOC Tritron [44] and demonstrated the validity of the concept by accelerating $^{32}S^{14+}$ ions up to 72 MeV [45].

SEPARATE-SECTOR CYCLOTRONS

The separate-sector (SS) cyclotron, proposed by Willax [46], is also widely used for heavy ions. Table 3 summarizes the heavy-ion SS cyclotrons currently in operation. The introduction of open (magnet-less) valleys between sector magnets produces high-flutter isochronous magnetic fields and sufficient spaces for high-acceleration-voltage cavities to be installed. High-flutter magnetic fields induce sufficient vertical focusing for 100*A*-MeV ions, so the SS cyclotrons in Table 3 are all of the radial sector type except for RCNP Ring Cyclotron, which is designed to accelerate proton beams up to 400 MeV. The high-voltage acceleration cavities produce a larger turn separation at beam extraction than compact cyclotrons do, which is beneficial for safe extraction of high-power beams. On the other hand, the SS cyclotron is much larger and its construction cost is much higher in comparison with a compact SC cyclotron with comparable bending power.

Table 3: Specification of heavy-ion separate-sector cyclotrons. Compiled data in [2] are used except for the acceleration voltages of HIRFL [47] and GANIL [19]. RIBF fRC, IRC, and SRC use single gap cavities.

Facility & machine	K_B (MeV)	No. of sectors	Spiral angle (deg.)	Hill gap (cm)	No. of dees	V_{gap} (kV)	Frequency (MHz)	Injector
HIRFL SSC	450	4	0	10.0	2	200	6.5–14	SFC
GANIL CSS1	380	4	0	10.0	2	160	7–13.45	C01 / C02
GANIL CSS2	380	4	0	10.0	2	250	7–13.45	CSS1
RCNP Ring	400	6	30	6.0	3	375	30–52	RCNP-AVF
HZB K130	132	4	0	6.0	2	140	10–20	Tandetron
iThemba LABS SSC	200	4	0	6.6	2	230	6–26	SPC1 / SPC2
RIBF RRC	540	4	0	8.0	2	270	18–40	AVF/RILAC/RILAC2
RIBF fRC	700	4	0	5.0	2	450	54.75	RRC
RIBF IRC	980	4	0	8.0	2	700	18–38	RRC / fRC
RIBF SRC	2600	6	0	70.0	4	650	18–38	IRC

GANIL

GANIL has operated a high-power cyclotron complex since 1982 [48]. Either of the two compact injectors C01 and C02 (K_B = 28 MeV) serves as an injector of the second-stage cyclotron CSS1. Extracted beams from CSS1 are charge-stripped before being injected into the final-stage cyclotron CSS2. In this scheme, light ions are accelerated up to 95*A* MeV. 10^{12}-pps light ion beams were obtained just after commissioning and a series of upgrade programs (OAE [49], OAI [50], THI [51]) was conducted to obtain higher energies for heavy ions, higher intensities, and so on. The ECR ion source serving beams to C01 is installed on a high-voltage platform. Its maximum extraction voltage is 100 kV in total. The axial injection line to C01 and its central region are designed to accept large emittance (60π mm-mrad) beams and to fulfill 6D phase-space matching [52, 53]. Turn separations at C01 and C02 are sufficiently large. Relatively low-charge-stage ions are accelerated up to CSS1 and the ions are charge stripped only once before CSS2 at higher energies. All these contribute to the high-intensity beams obtained by GANIL. The beam power obtained is 5 kW [54].

HIRFL IMP (Lanzhou), RCNP, iThemba LABS

A unique feature of the HIRFL cyclotron complex comprising the SFC (K_B = 69 MeV) and SSC [55] is that these cyclotrons are used as injectors to a cooler-storage ring complex, CSRm and CSRe [56]. Light ions accelerated by SFC can be injected directly into CSRm via charge stripping or multiple multi-turn injection schemes. Heavy ions obtained by SSC coupled with SFC are also injected into CSRm. Nearly 10^{10} ppp ions are injected, accumulated, cooled, and accelerated up to 600*A* MeV in CSRm. The accelerated ions are fast extracted and then used to produce RI beams at the fragment separator RIBLL2. The RI beams injected into CSRe are used for precise mass measurements of exotic nuclei and so on. A new linac injector to SSC is now under construction to further upgrade the intensity at SSC [57].

The RCNP cyclotron cascade consists of an AVF (K_B = 140 MeV) cyclotron and the Ring cyclotron. It has been providing ultra-high-quality light ion beams. The cascade was upgraded to increase beam currents and ion variety. A flat-top acceleration cavity was introduced into the AVF cyclotron, and a 18-GHz SC ion source was also introduced [58]. RCNP have been developing magnets utilizing high-temperature superconducting wires [59].

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iThemba LABS has proposed constructing a RI beam facility where its SPC2 and K200 cyclotron complex is used as a post-acceleration system [60].

RI Beam Factory (RIBF)

RIBF consists of two injector linacs (RILAC [61] and RILAC2 [62]), an injector AVF cyclotron (K_B = 70 MeV) [63], three conventional SS cyclotrons (RRC [64], fRC [65] and IRC [66]), and the world's first superconducting SS cyclotron SRC [67]. RILAC2, fRC, IRC, and SRC were newly constructed in the RIBF project, which started in 1997. The remaining accelerators have been used for over 25 years. Very light ions can be accelerated up to 400*A* MeV with a combination of AVF + RRC + SRC. Light and medium-heavy ions are also accelerated to 400*A* MeV using RILAC, RRC, IRC, and SRC in series (variable energy mode). Very heavy ions such as xenon and uranium are accelerated in a fixed-energy mode where RILAC2, RRC, fRC IRC, and SRC are used in series. The beam energy is fixed to 345*A* MeV in this mode, because RILAC2 and fRC are fixed-frequency machines. Beam intensities obtained for light ions are 1 pμA, limited by current radiation safety regulations. For medium-heavy ions, 0.53- and 0.49-pμA beams were obtained for 345*A*-MeV ^{48}Ca and ^{78}Kr, respectively. The beam power of ^{78}Kr reaches 13 kW. Performance of the fixed energy mode has steadily improved. The present intensity of a 345*A*-MeV ^{238}U beam is 40 pnA. Beam availability, defined as the ratio of actual beam service time to scheduled beam service time, exceeded 90% in these two years.

The present performance of RIBF does not fully utilize the potential of the newly constructed cyclotron cascade, in that these cyclotrons are operated far below their space charge limits, especially for very heavy ions. One reason is that RIBF adopts a two-stage charge-stripping scheme when accelerating beams up to 345*A* MeV. The total charge-stripping efficiency for uranium ions is only 5.5%. In the case of ^{48}Ca, ions are charge-stripped twice, with the first stripping performed at 2.7*A* MeV, much lower than NSCL-CCF and GANIL. If we apply the fixed energy mode to medium-heavy ions, we can skip the first-stage charge stripping thanks to the 28-GHz SC ECRIS [68]. We thus successfully obtained a 13-kW ^{78}Kr beam, but its beam quality was worse than that obtained in the variable energy mode. Elaborate tuning of the accelerator complex and a more reliable beam interlock system are essential for the 30-kW operations envisaged for the near future.

SUMMARY AND FUTURE

Worldwide activities concerning heavy-ion cyclotrons now cover energy ranges up to 345*A* MeV for all ion species, despite construction of new heavy-ion cyclotrons slowing and nonnegligible activities related to accelerating heavy ions being phased out or significantly reduced at several facilities. Examples of the beam intensity obtained so far are 10 pμA for very low-energy beams ($E \leq 1A$ MeV) or very light ions such as lithium, at the level of 1 pμA (0.5–2 pμA) for light and medium-heavy ions with energies up to 345*A* MeV, and less than 0.1 pμA for high-energy very-heavy ions such as uranium. DC-280 of FLNR JINR plans to extend the 10-pμA region up to 5*A*–6*A* MeV for medium-heavy ions, which is a good example of a future high-performance heavy-ion cyclotron dedicated to specific applications.

Many facilities are making efforts at improving the efficiency of injection into cyclotrons and understanding beam behaviors more precisely in low-energy regions. Further intensity upgrades are possible if heavy-ion cyclotrons fully utilize the recent high performance obtained in so-called third-generation ECRISs that can produce beams of hundreds of micro-amperes with intrinsic emittance areas exceeding 150π mm-mrad.

Cyclotrons have long been the energy-frontier accelerator operated in CW mode. Realizing a cyclotron accelerating heavy ions up to 0.7*A*–1*A* GeV is a rational challenge, although isochronous cyclotrons of the existing types will seriously suffer from difficulties in both vertical focusing and turn separation at beam extraction under highly relativistic conditions as $E > 1A$ GeV.

Finally, the large-scale SC linac complexes [69, 70] plan to cover in the near future nearly the whole operating region (as defined by ion species and beam energy) of existing heavy-ion cyclotrons with higher beam intensities. However, this does not mean that these SC linacs can cover all the present activities of existing heavy-ion cyclotrons. Good synergetic effects from these SC heavy-ion linacs are expected.

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