# HIGH INTENSITY OPERATION FOR HEAVY ION CYCLOTRON OF HIGHLY CHARGED ECR ION SOURCES*

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*Abstract*

ECR ion sources have been used as the primary high charge state ion beam injector for cyclotrons for more than 30 years. With the persistent efforts of ECRIS researchers, many high performance ECR ion sources have been built globally, which are capable of producing intense high charge state ion beams. Modern advanced ECR ion source can provide stable and reliable high charge state ion beams for the routine operation of a cyclotron, which has made it irreplaceable, particularly with regard to the performance and efficiency that a cyclotron complex could achieve with the ion source. The 3rd generation ECR ion sources that can produce higher charge state and more intense ion beams have been developed and put into cyclotron operation since early 21st century. They have provided the privilege for the cyclotron performance improvement that has never been met before, especially in term of the delivered beam intensity and energy, which has greatly promoted the experimental research in nuclear physics. This paper will have a brief review about the development of modern high performance high charge state ECR ion sources. Typical advanced high charge state ECR ion sources with fully superconducting magnet, such as SERSE, VENUS, SECRAL, SuSI and RIKEN SC-ECRIS will be presented, and their high intensity operation status for cyclotrons will be introduced as well.

## INTRODUCTION

ECRIS (Electron Cyclotron Resonance Ion Source) which is the most efficiency machine to deliver CW or long pulsed highly charged heavy ion beams, has already become an indispensable injector for modern cyclotrons since its first application on the Karlsruhe cyclotron in 1981 [1]. Operation of heavy ion cyclotron needs intense highly charged stable and reliable high quality heavy ion beams, which are typical features that a high performance ECRIS can meet. Nuclear physics research needs high quality, high power, high duty factor ion beams. Cyclotron was a very unique tool for nuclear physics research in last century. The development of cyclotrons has boosted the research activities enormously, and the application of ECRISs with cyclotrons has further promoted the advancement. The main driven force for the development of ECRISs in the 80s and 90s last century was the strong requirements from cyclotron operation for intense high quality highly charged heavy ion beams. After the successful connection of the so-called 1st generation ECRIS PICOHISKA to a cyclotron [1], many innovative techniques have been made by the Grenoble team and other researchers around the world, which made ECRISs more feasible to be employed on cyclotrons. The real breakthrough was the success of Caprice sources in the middle of 1980s [2], which are still widely used on cyclotrons. Caprice source is just the typical example of the 2nd generation ECRISs. In the succeeding 10 years, many prominent sources have been built, such as the ECR4 in GANIL [3], A-ECR in LBNL [4], RIKEN 18 GHz ECRIS [5], and so on. These nice performing machines have helped improve the cyclotrons' performances that have never been met before. Thanks to the great advancement of NbTi superconducting technique, the fabrication of the 3rd generation ECR ion source is possible and cost efficient. SERSE ion source is just a 2.5th generation one with a fully superconducting magnet that enables the source to work at high B mode [6]. Nevertheless, it has provided many technical or theoretical references to later 3rd generation ECRISs such as VENUS in LBNL [7], SECRAL in IMP [8], SuSI in MSU [9], and SCECRIS in RIKEN [10]. Actually, the 5 superconducting ECRISs listed above are all now in routine service as primary heavy ion beam injectors for cyclotrons. These high performance ECRISs can produce very intense heavy ion beams of high charge states that have remarkably pushed the performance of the connected cyclotrons towards the high limit. This paper will give a general presentation on the high intensity operation status of highly charged ECRISs for heavy ion cyclotrons. Although there are so many cyclotrons using high charge state ECRISs as ion beam injectors, as examples, this paper will mainly cover the work in GANIL, INFN-LNS, LBNL, MSU, RIKEN and IMP.

## GANIL SOURCES

ECRIS was installed as one of the GANIL injector ion sources in 1985. Several years later, both of the injectors were equipped with room temperature ECRISs working alternatively to produce stable primary ion beams at GANIL. ECR4 and ECR4M are typical 2nd generation ECRISs working at high B mode that enables the high yield of highly charged ion beams. The refined structure ECR4 type ion sources can incorporate external feedings of solid material to the plasma with different techniques, such as inserted rod, resister oven, sputtering sample and MIVOC. The schematic picture of ECR4 ion source is given in Fig. 1. The GANIL injector ion sources can provide highly charged ion beams of all heavy elements from carbon to uranium. Till now, highly charged ion beams from more than 50 isotopes have been delivered. ECR4 is connected to a K25 cyclotron C01 and delivers heavy ion beams with the maximum energy of 100 keV/q by floating the ion source and the beam selection line on a 100 kV high voltage platform. ECR4M is connected to

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ISBN 978-3-95450-128-1

another K25 cyclotron C02 and injects it with maximum ion beam energy of 25 keV/q. Higher beam energy can lower beam emittance growth during transmission. The transmission from ion source to cyclotron, C01 injector has better efficiency with the help of the 100 kV high voltage platform. Different from the other 5 laboratories to be discussed here, ECRIS is also used to produce multiple charge state radioactive ion beams for post-accelerator purpose in GANIL. Radioactive isotopes produced in the target are ionized by a permanent magnet ECRIS and the produced ion beams are injected into CIME cyclotron for post-acceleration. And as an upgrade project of SPIRAL1, a 1+ to n+ charge breeder system based on ECRIS technique will be installed to further improve the efficiency and performance [11].

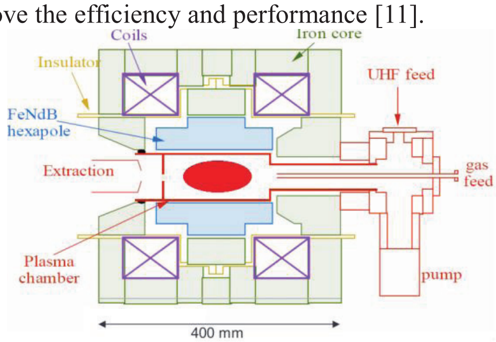


Figure 1: Schematic plot of ECR4 ion source.

## INFN-LNS SOURCES

In INFN-LNS, the K800 superconducting cyclotron CS was working as a booster of the old Tandem back to the 1990s. The operation of the two coupled accelerators was a bit clumsy. A lot of time was required to tune to make the coupling possible, and this coupling operation was also not very stable. The installation of the state of the art ion source SERSE in 1999 made the stand along operation of CS possible. This strategy has greatly improved the performance of this accelerator facility.

SERSE is a fully superconducting ECRIS built under the collaboration between CEA/Grenoble and INFN-LNS [6]. SERSE was tested to produce the first ion beam in 1997. The ion source was designed with the concept of high microwave frequency, high B mode, high mirror ratio, big plasma chamber, which were derived from the semi-experience laws based on the work in the last 20 years. Although SERSE is not the first fully superconducting ECRIS ever built, it is the first high performance ECRIS built with NbTi superconductor. The subsequent source commissioning results validated the effectiveness of the concept. SERSE can produce both metallic and gaseous ion beams with high intensity at 18 GHz, such as 84 eμA $Ar^{14+}$, 66 eμA $Kr^{22+}$, 38.5 eμA $Xe^{30+}$, 20 eμA $Au^{30+}$ and 0.03 eμA $Au^{42+}$. A remarkable work completed with SERSE was the test of 28 GHz microwave ECR heating to produce more intense highly charged ion beams. In 2000, a 28 GHz/10 kW microwave generator was connected to SERSE to have a plasma density inside the plasma chamber up to $10^{13}.cm^{-3}$. The test was very profound. Many world record beam intensities were made, such as 100 eμA $Xe^{30+}$, 8 eμA $Xe^{38+}$, 0.5 eμA $Xe^{42+}$, which was not renewed until 2006 by VENUS and SECRAL. With the availability of 28 GHz, 18 GHz, and 14 GHz microwave power heating, the ion source was used to have experimental check the validity of the scaling laws invented by R. Geller. The refined scaling laws with the test results from SERSE and the test scheme of 28 GHz microwave power transmission and coupling provides fruitful references to the high performance ECRISs built later on.

SERSE and a room temperature CAESAR are now operating on shift as heavy ion beam injectors for CS. CAESAR is an upgraded model of the Caprice type ECRIS, and mainly used to produce lighter heavy ion beams to the cyclotron, whereas SERSE has been mainly devoted to the production of highly charged heavy ion beams. Fig. 2 is the picture of SERSE installed to the injector beam line.

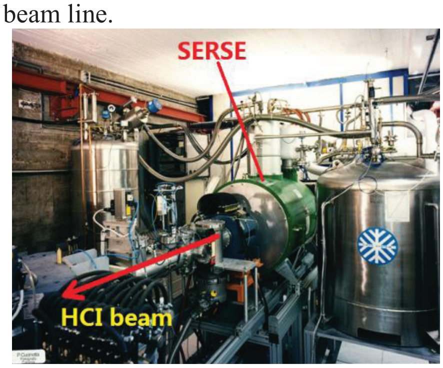


Figure 2: SERSE source installed to injector beam line.

## LBNL SOURCES

In LBNL, the famous 88-inch K140 sector-focused cyclotron is still in good service condition with the three primary beam injectors, 6.4 GHz LBL ECR [12], 14.5 GHz AECR-U [4] and 28 GHz VENUS [7]. ECRIS was installed to 88-inch cyclotron as the heavy ion beam injector in 1984 with the great effort by Claude Lyneis. The listed ECRISs in 88-inch lab are giving the exhibition of ECRIS development in LBNL. The 6.4 GHz LBL ECR is one of best performing 1st generation ECRIS back to the 1980s. The 14.5 GHz AECR-U is a 2nd generation ECRIS developed with very unique structure in 1990s. And the 28 GHz VENUS is now one of the best performing 3rd generation in operation. The three ion sources are in shift routine operation with the 50 years old cyclotron to deliver large variety of intense energetic ion beams for nuclear research. Actually, the main working horse now is VENUS ion source that can deliver more intense and higher charge state ion beams.

In LBNL, back to the middle of 1990s, AECR-U designed with the high B mode, radial pumping method and innovative dual-frequency heating technique has boosted the performance of ECRIS enormously, especially the production of very heavy highly charged ion beams, such as 0.5 eμA $Au^{47+}$, 0.15 eμA $Bi^{50+}$ and 0.02 eμA $U^{55+}$. With the highly charged ion beam injection from AECR-U, the acceleration of 13.6 MeV/A xenon beam and 8.13 MeV/A uranium beam was succeeded on this K140 cyclotron.

VENUS ion source is the first 3rd generation ECRIS built that enables an optimum operation condition at 28 GHz. Supported by DOE, VENUS also served as the prototype ion source for RIA project. It was successfully assembled in 2001 and gave the first analysed ion beam at 18 GHz in September 2002. Very promising results at 28 GHz was achieved in 2005. The B-min field of this ion source is provided by 3 axial solenoids and a radial sextupole magnet winded with NbTi wires and bathed in 4.2 K LHe during operation (as shown in Fig. 3), which comes with a maximum axial mirror peak field of 4 T and a maximum radial field 2.1 T at the inner wall of 150 mm ID plasma chamber. In 2006, a recorded uranium beam intensity of 220 eμA $U^{33+}$ was produced at a 28 GHz + 18 GHz ECR heating mode. In the same year, VENUS had been coupled to the 88-inch cyclotron with several eμA of $U^{47+}$, and tens of enA of $Xe^{42+}$. The cyclotron output energy of xenon ion beam was renewed by 14.0 MeV/A and the intensity of uranium beam was also greatly boosted. Continuous improvement of the ion source and the associated techniques has made the source performance advancement possible. In 2011, 450 eμA $U^{33+}$ and 400 eμA $U^{34+}$ had been produced which set a new world record to uranium beam production [13]. An outstanding work has been accomplished with VENUS at LBNL recently after its long maintenance shutdown. It had been used to deliver averagely 78 eμA $^{48}Ca^{11+}$ to the cyclotron for 60 days straight from April to June 2013. The average consumption rate of 0.25 mg/hr had been achieved that enabled a very cost efficient experiment at 88-inch cyclotron [14]. And because of the capacity of producing very highly charged heavy ion beams, many combinations of cocktail beams had been prepared with the plasma yield of VENUS.

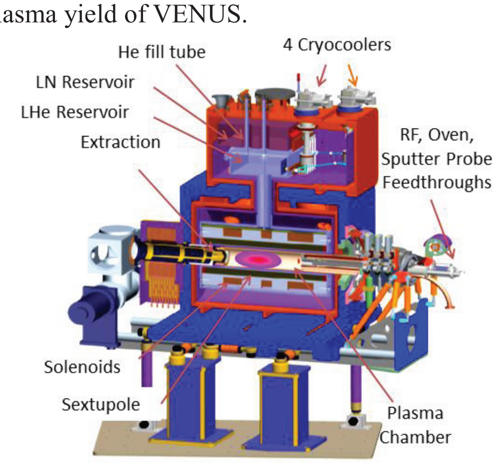

Figure 3: Sectional picture of VENUS source.

## MSU SOURCES

ECRIS was employed to the NSCL/MSU cyclotron system in 1985 by T. Antaya. Several other ECRIS had been built later as the primary ion beam injector for the cyclotrons, including the well-know 6.4 GHz fully superconducting ion source SC-ECR [15]. The NSCL superconducting cyclotrons K500 and K1200 were built in 1980s and early 1990s correspondingly. Originally, they were built as stand along operation machines. But at that time, the available ECRISs couldn't meet the K1200 needs with sufficiently high beam intensities of desired charge states. Therefore, the two cyclotrons and the injection lines had been modified and designed as coupled accelerator complex CCF, i.e. K500 serves as the injector machine for K1200, which had been proven very successful [16]. CCF is now served with two primary beam injector ion sources: a room temperature AECR-U type 14.5 GHz Artemis and a fully superconducting ECRIS SuSI working at 18 GHz.

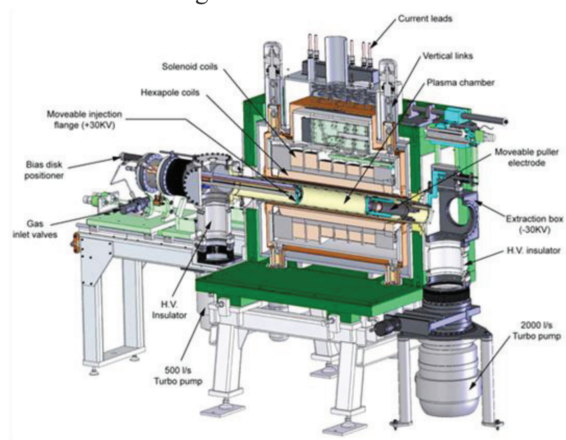

Figure 4: Sectional picture of SuSI source at NSCL.

SuSI was designed and fabricated in NSCL/MSU. The axial magnetic field were designed to have a full flexibility, allowing tuning the axial field mirror strength, mirror length, $B_{min}$ value and position, field gradient at both ECR points, and the shape of field distribution between the two ECR points. This design nominally can give a great flexibility to optimize the field for high charge state ion beam production. Additionally, very useful techniques such as axially movable injection baffle, axially movable biased disk, movable triode extraction system, are all incorporated in the design of SuSI, which makes SuSI a very good machine to test highly charged ion beam production. Fig. 4 gives the sectional view of SuSI ion source design. SuSI was successfully built in 2007 and gave the first analysed beam with 18 GHz ECR heating the same year. The magnet was fully trained to have a maximum mirror peak field of 3.4 T and a maximum radial field of 2.0 T at the 101 mm ID plasma chamber wall. Since SuSI has a maximum plasma chamber volume of 3.5 litres, fed with two 2 kW maximum output microwave power 18 GHz klystrons, it is the only 3rd generation ECRIS that can reach the ECR heating power density higher than 1.0 kW/L, which enables the production of 735 eμA $Ar^{11+}$, 308 eμA $Ar^{14+}$, 500 eμA $Xe^{26+}$, 110 eμA $Xe^{30+}$, 320 eμA $Bi^{30+}$ and 196 eμA $U^{33+}$ even at 18 GHz. A program to upgrade SuSI to 24 GHz is now undergoing.

SuSI operation was interrupted by unknown reason random quenches in 2007, but was back to normal in




ISBN 978-3-95450-128-1

2008. It was connected to CCF and put into routine operation in 2009. Beyond any doubts, SuSI can provide more than enough medium charge state ion beams for the cyclotron injection. However the injection line of SuSI for CCF is unique in comparison to the others in operation. A collimation channel system (Fig. 5) was adopted in the injection LEBT line, which only allows ion beam with selected quality for injection [17]. This application can obviously ease the operators' work to optimize the beam from ECR ion source for injection, which is not always guaranteed with needed quality. SuSI is now served as the main working horse for heavy ion beam operation. No quenches was detected during the routines.

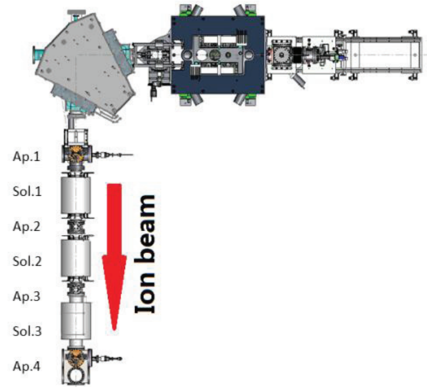


Figure 5: SuSI ion source and the collimation line.

## RIKEN SOURCES

In 1988, a 10 GHz ECRIS based on the 6.4 GHz LBL ECR design was successfully fabricated and extracted the first analysed ion beam. This ion source was used as one of injector ion sources for the K70 AVF cyclotron in RIKEN [18]. Several other high charge state 2$^{nd}$ generation ECRISs had been developed successively in the 1990s and early 2000s [5]. The 18 GHz RIKEN ECRIS built in 1995 is the representative one because of the promising results and the new ECRIS techniques incorporated. The ion source was designed with a high B mode concept, allowing a maximum mirror ratio of 3.0, and a hexapole tip field of 1.4 T. Aluminium liner and even $Al_2O_3$ plating for plasma chamber inner wall condition modification had been tried. Plasma electrode position had also been changed for incident charge state optimization. Eventually, very intense medium charge state ion beams had been extracted with the source operation at 700 W/18 GHz, such as 0.3 emA of $Xe^{20+}$, 0.6 emA of $Kr^{13+}$ and 2 emA $Ar^{8+}$.

To meet the final project goal of RIBF, a more powerful ECRIS is needed which can produce 15 puA $U^{35+}$ so as to achieve 1 puA 350 MeV/A uranium beam after the SRC [10]. Therefore, the RIKEN SC-ECRIS project was proposed, aiming to build a fully superconducting ECRIS optimized for the operation at 28 GHz/10 kW. Similar to the SuSI ion source, the axial field is a superposition of the fields excited by six independent axial solenoids, so as to have a full flexibility of the axial field configuration as discussed for the SuSI ion source design. The mirror field peaks are 3.8 T at source injection side and 2.2 T at source extraction side, which are separated by a mirror length of 50 cm. The strong radial sextupole coils provide a 2.1 T maximum field at the 15 cm ID plasma chamber inner surface. The schematic drawing of the ion source is given in Fig. 6. To enable safe operation of the source at high 28 GHz microwave power heating, SC-ECRIS has been installed with 2 GM-JT and 1 GM 4.2 K coolers that can mitigate a dynamic heat load of 8 W from the 4.2 K cryostat caused by the hot plasma bremsstrahlung radiation. With the help of Mitsubishi Electric, the complicated superconducting magnet was fully available in about 2 years. The first plasma at 18 GHz was obtained in early 2009, and it was soon put into routine operation for the cyclotrons.

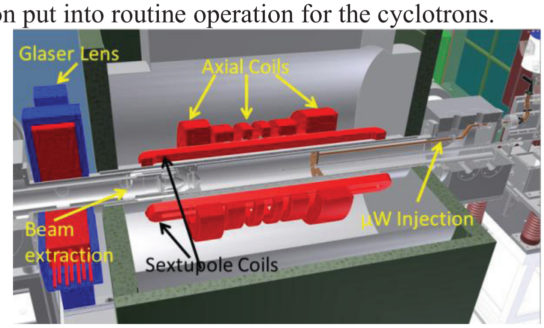


Figure 6: Schematic picture of RIKEN SC-ECRIS source.

In RIKEN Nishina center, there are three primary ion beam operation modes for the BIBF facility. The AVF mode is using a polarized ion source, the 18 GHz LHe-free hybrid superconducting SHIVA source, and a 14.5 GHz room temperature source as polarized deuteron beam or low mass ion beams injectors for AVF cyclotron. The variable energy mode is realized with the injector combination of the RIKEN 18 GHz ECRIS and RILAC accelerator, which is aiming to provide the ion beams of medium weight isotopes. The Fixed-energy mode is achieved with a combination of the 28 GHz RIKEN SC-ECRIS and the recently built RILAC2 accelerator, which is mainly used to deliver intense heavy ion beams from xenon to uranium. At 28 GHz, SC-ECRIS is able to produce more than 230 eμA $U^{33+}$ and 180 eμA $U^{35+}$ with U rod sputtering method. More than 80 eμA $U^{35+}$ has been used in routine operation for almost 2 months, and a reasonable consumption rate of 4 mg/h has been achieved.

## IMP SOURCES

In 1988, the first ECRIS: a 10 GHz Caprice ECRIS bought from CEA/Grenoble, was introduced to IMP. Based on this source, a 10 GHz LECR1 source was later developed and connected to the K69 SFC cyclotron. Based on the concept of Caprice type ion source and GANIL ECR4, a 14.5 GHz LECR2 ion source was built in 1997 with a high B mode, and techniques like aluminium plasma chamber liner, aluminium plasma electrode were utilized. More importantly, with MIVOC and micro oven methods, highly charged metallic ion beams were available to HIRFL facility for the first time. LECR2 was put into routine operation in 1999. Another room temperature source LECR3 was built 3 years later as an upgrade machine of LECR2 but with higher fields and bigger plasma chamber [19].

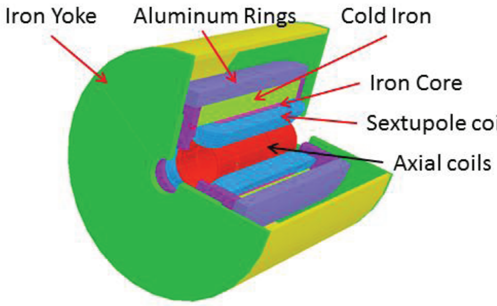


Figure 7: Sectional view SECRAL source magnet body.

At IMP, two cyclotrons are in operation, i.e. the K69 SFC and K450 SSC. They were successfully put into operation in 1980s. They are now operated as coupled cyclotrons, but the coupling efficiency is fairly poor. SFC was originally designed in the 1960s, aiming to deliver MeV/A light mass ion beams such as proton and deuteron beam. To achieve the coupling operation mode, especially for heavy ion beams, very high charge states are desired. And with the completion of the CSR synchrotron project, the accelerator facility will be operated with SFC, SFC + CSR or SFC+ SSC + SCR modes, which extremely need high intensity high charge state heavy ion beam injection. Therefore, the fully superconducting ECRIS SECRAL project was funded and the magnet body was available in 2005 with the help of former ACCEL Inc. The SECRAL magnet body was designed with a reversed structure in comparison with traditional one, such as VENUS [7] and SERSE [8]. The sextupole magnet is placed external to the axial solenoids, which makes this source very unique, very compact and also cost efficient one amongst the 3$^{rd}$ generation ECRISs. The magnetic structure is given in Fig. 7. The 3 axial solenoids can provide a maximum 3.7 T mirror field along the axis. The maximum radial field at the inner wall of Ø126 mm ID plasma chamber wall is 2.0 T. The first analysed beam was obtained in 2005 with 18 GHz microwave heating. With a maximum of 3.2 kW 18 GHz microwave (from 2 klystrons) power heating, many world record beam intensities were obtained. In 2009, the source was upgraded to 24 GHz. The maximum RF power ever tried into the 5 L plasma chamber was about 5 kW. At a power density level of 1 kW/L, 455 eμA $Xe^{27+}$, 236 eμA $Xe^{27+}$, 0.1 eμA $Xe^{45+}$, 422 eμA $Bi^{30+}$ and 396 eμA $Bi^{31+}$ have been produced. SECRAL is now serving the HIRFL accelerators together with other two ECRISs: LECR3 and LAPECR1. LAPECR1 is used to provide intense proton or $H_2^+$ beams, and LECR3 is mainly used for medium mass ion beams. SECRAL is the only injector for highly charged heavy ion beams from Xe to U with beam intensities around 100 eμA.

## CONCLUSIONS

There are also many other cyclotron labs who are using ECRISs as the injector for intense highly charged ion beams. And each of them can present a successful example on how to incorporate high performance ECRISs to a cyclotron machine and make the design goal possible, performance improved. Although there are many projects going on globally to build high power heavy ion beam machine, the combination of high performance ECRIS + powerful cyclotrons is still the most powerful CW heavy ion beam machine so far.

## ACKNOWLEDGEMENT

The author would like to thank P. Jardin, C. Luigi, J. Benitez, G. Machicoane, T. Thuillier and T. Nakagawa for their fruitful suggestions.

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