

# ALL PERMANENT MAGNET ECR ION SOURCE DEVELOPMENT AND OPERATION STATUS AT IMP

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## Abstract

All permanent magnet ECR ion sources have many advantages over traditional ECR ion sources composed of several axial room temperature solenoids and one permanent magnet hexapole magnet, which make them the first choice for many heavy ion facilities and platforms. At IMP, three all permanent magnet ECR ion sources have been built for different applications, i.e. the very compact ECR ion source LAPECR1 for intense mono or multi charge state ion beams' production, the LAPECR2 ion source installed on the 320 kV high voltage multidisciplinary platform, and the LAPECR3 ion source dedicated to C<sup>5+</sup> beam production for the cancer therapy facility. In this paper, after a general discussion of the ion sources' design, the applications and the operation status of the IMP all permanent magnet ECR ion sources will be presented.

## INTRODUCTION

Been widely used as Multiple Charge Ion (MCI) beam provider, ECR ion source is one of the best devices that can produce intense MCI beams. ECR ion source is actually a magnet field confined plasma machine, where the ion beams can be extracted. The confinement magnetic field is normally a so-called nested min-B magnetic field which is a superposition of radial multipolar field and axial mirror field. Generally, the axial field is supplied by superconducting magnet solenoids, room temperature magnet solenoids, or permanent magnet rings, while the radial field is supplied by either superconducting sextupole coils or Halbach structure permanent magnet hexapole [1] (other hexapole structures are also used). The different combination of the types of radial and axial field magnet gives the different species of ECR ion sources, i.e. fully superconducting ECR ion sources, such as VENUS [2] and SECRAL [3], hybrid ECR ion sources, such as SHIBA [4] and A-PHOEBIX [5], classical room temperature ECR ion sources, such as AEER-U [6] and GTS [7], and all permanent ECR ion sources, such as the Nanogan sources [8] and the BIE sources [9]. The first very successful modern ECR ion source, the so-called Caprice source [10], is a room temperature ECR source, which is still widely used in many labs. Fully superconducting ECR ion sources can provide the beam intensities and charge states that can't be met by other types of ECR sources, but based on the applications, all the four types of ECR ion sources can

find the users if only the application needs can be met. All permanent magnet ECR ion sources have their special features and merits that make them extremely suitable for industrial applications and small experimental platform setup: (1) very compact device, (2) easy maintenance, (3) easy to operate, (4) low electricity consumption, (4) no needs for large volume LCW (Low Conductivity Water), and (5) most important of all, cost saving. But there also several intrinsic disadvantages of this type of devices mostly because of the all permanent magnet structure, such as: (1) inflexibility of the magnetic field, (2) low magnetic field strength and small plasma chamber size, and (3) therefore moderate MCI beam intensity.

IMP/CAS is an institute dedicated to nuclear physics and the associated multidisciplinary physics studies. The accelerator facility development is based on these needs and requirements. Three all permanent magnet ECR ion sources have been successively built at IMP for the facility's needs. The structure and the parameters will be discussed in the following content.

## LAPECR1 SOURCE

Small experimental lab needs very compact experimental setups. This is the original reason to build the LAPECR1 source to deliver intense mono charge state ion beams, low intensity MCI beams and even some molecular ion beams. Table 1 gives the main parameters of this ion source. This ion source is designed with a very compact size which makes the source body weighs only 25 kg that can be easily moved around by an adult. Despite of the compactness, the source is equipped with a Ø40 mm ID plasma chamber that enables the direct microwave power feeding with a WR62 rectangular waveguide to simplify the injection plug structure. Iron plugs at both the injection and extraction sides have been incorporated to enhance the mirror peaks. The source is designed and operated at 14.5 GHz.

HIRFL accelerator needs intense proton and H<sub>2</sub><sup>+</sup> beams for ion beam injection. The room temperature LEER3 ion source, which is mostly used to deliver intense MCI beams like C<sup>4+</sup>, Ar<sup>8+</sup>, Kr<sup>18+</sup>, Xe<sup>20+</sup> and etc., can't be operated at the source potential higher than 25 kV, therefore a simple setup that can deliver intense proton or H<sub>2</sub><sup>+</sup> beams at the source potential of ~35 kV is proposed. In this project, LAPECR1 is floated on a G10 insulator plate which is covered with a plexiglass box. Because of the simple structure of LAPECR1, this setup composes a small HV platform that can be biased to more than 36 kV.

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28-35 kV has been tested for routine operation. This project has been completed by the end of July, 2012. With only tens of watts microwave power feeding, very stable intense  $\sim$ emA proton and  $H_2^+$  beams have been produced. Long term beam intensity fluctuation is observed to be reasonably good with a value of  $\sim$ 0.2%. Fig. 1 is the picture of the LAPECR1 source rested on the small HV platform.

Table 1: Main Parameters of LAPECR1

$B_{inj}$	1.0 T
$B_{ext}$	0.56 T
Hexapole pole surface	1.1 T
Plasma chamber ID	40 mm
$f$	14.5 GHz
Dimension	$\Phi$ 102 mm $\times$ 296 mm
Weight	$\sim$ 25 kg
Permanent material	N45M NdFeB
$L_{mirror}$	74 mm
$L_{ECR}$	55 mm
HV	30~50kV



Figure 1: LAPECR1 source installed on a HIRFL injection beam line.

## LAPECR2 SOURCE

The HIRFL accelerators can provide the beam energies covering several MeV/u to hundreds of MeV/u. Multidisciplinary physics research needs much wider energy range for various studies. A 320 kV HV platform was proposed in 2002 and completed in 2006. A high charge state all permanent magnet ECR ion source LAPECR2 has been built and installed on the platform to deliver intense ion beams. Based on the users' requirements, ion beam species from low to high charge states of gaseous or solid elements are required. For the purposes, the source was designed to operate at high magnetic field, high frequency mode. Table 2 lists the main parameters of LAPECR2 source in comparison with

a classical room temperature LECR2 ion source [11] operated at the same frequency of 14.5 GHz.

LAPECR2 is designed with all permanent magnet structure. No iron plug has been used to boost the mirror fields because of the difficulties to handle the strong magnetic force during the installation. To produce intense high charge state ion beams, the plasma chamber is intentionally designed as big as possible. A tradeoff between the magnet compactness and the magnetic field strength makes  $\Phi$ 67mm the final plasma chamber ID value. The axial magnetic rings are specially designed with conical shape inner bore structure to achieve wanted axial field profile, and the hexapole magnet is also designed with conical shape on both sides to have sufficient radial confinement magnetic field inside the plasma chamber. For this design, there have been some difficulties and problems during the magnet fabrication, for example the edge of the conical shape magnet blocks are easily broken because the NdFeB magnetic blocks are very fragile and the edge is very sharp and flimsy. Nevertheless, the magnet has been successfully built and tested.

Table 2: Main Parameters of LAPECR2 in Comparison with LECR2 Ion Source

Parameters	LAPECR2	LECR2
Axial Mirror Peaks (T)	1.28, 1.07	1.5, 1.1
$B_{min}$ (T)	0.42	0.39
$B_{rad}$ (T)	1.21	1.0
Hexapole Material (NdFeB)	36-segmented N45M	24-segmented N42
$\mu$ W Frequency (GHz)	14.5	14.5
$\mu$ W Power Coupling Mode	Off-axial Direct	Coaxial
$L_{mirror}$ (mm)	255	265
$L_{ecr}$ (mm)	100	86
Plasma Chamber ID (mm)	67	70
Chamber Material	316 L SS	316 SS

During the machine commissioning, the source was fed with maximum 1.1 kW 14.5 GHz microwave power from a klystron amplifier to achieve high power density inside the plasma chamber. TWT microwave generator is of course a very good option that can provide flexibility in the microwave frequency tuning within a certain range to optimize source operation, which can compensate a little bit the magnetic field inflexibility disadvantage of an all permanent magnet structure source, but so far only 700W maximum output TWT machine is available, which is not enough for LAPECR2's  $\Phi$ 67mm ID plasma chamber. Both gaseous and solid materials have been fed into the plasma to produce intense medium charge state and high

charge state ion beams. Promising results have been obtained with LAPECR2 ion source. Fig. 2 gives the typical intensities of xenon ion beams in comparison with other devices working at similar frequencies. The performance has demonstrated that LAPECR2 source a well performing ion source that is comparable to even high performance room temperature ECR ion sources working at 14.5 GHz [12].

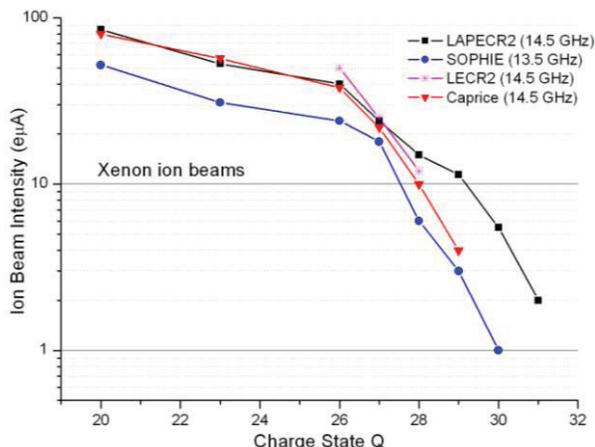


Figure 2: LAPECR2 xenon ion beam results in comparison with other 14.5 GHz ion sources.

LAPECR2 was put into operation on the 320 kV HV multidisciplinary platform in 2007. And it has been running on it to delivery various ion beam species for the 5 experimental terminals since then [13]. Fig. 3 is the picture of LAPECR2 source installed on the 320 kV HV platform. The HV platform has been tested to 395 kV, but for long-term operation stability and safety, the maximum allowed operation voltage is 320 kV. LAPECR2 together with the insulator support has been tested up to 28 kV, but due to the strong stray field and beam loss at source extraction side, the maximum safe operation voltage is lowered to ~23 kV for intense beam extraction. So, the nominal HV platform beam energy range is 5keV/q~340 keV/q which can cover a wide range of interesting physics. Till now, LAPECR2 has been used for routine operation more than 30,000 hours. Totally, 9 groups of gaseous elements including H, He, C, N, O, Ne, Ar, Xe, and Kr, and 9 groups of solid elements including Pb, bi, Fe, Eu, Mg, Cs, I, F and S ion beams have been delivered. Some of the results obtained during the experimental beam preparation are even much better than those obtained during the source commissioning test in 2006. Table 3 lists the typical beam intensities obtained during routine operation beam time. It is worth mentioning that most of the beam intensities were made with the microwave power of 400 W from a TWT microwave generator, since the footprint of a klystron amplifier is too big to be place on the HV platform.

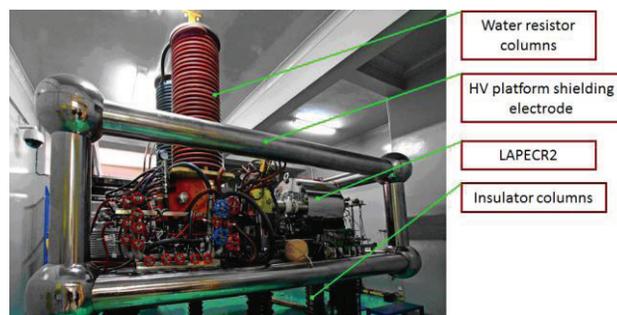


Figure 3: Picture of LAPECR2 ion source and the HV platform.

Table 3: Typical Delivered Ion Beam from LAPECR2 for Experimental Terminals

Ion Species	Results in 2006 (eµA)	During operation (eµA)
C <sup>5+</sup>	/	190
Ar <sup>16+</sup>	2	2
Kr <sup>23+</sup>	/	15
Xe <sup>30+</sup>	5.3	11
a)I <sup>25+</sup>	/	35
a)Cs <sup>16+</sup>	/	40
a)Cs <sup>23+</sup>	/	20
b)Fe <sup>13+</sup>	/	25
b)Fe <sup>15+</sup>	/	20
a)Eu <sup>30+</sup>	/	10
a)Eu <sup>33+</sup>	/	5
a)Bi <sup>28+</sup>	17	45
a)Bi <sup>31+</sup>	5	20
a)Bi <sup>33+</sup>	/	15
a)Bi <sup>36+</sup>	/	3

a) with resistor oven; b) with MIVOC ;

### LAPECR3 SOURCE

Based on the existing technology and the experience with HIRFL-CSR, a new accelerator complex named HITFiL or Heavy Ion Therapy Facility in Lanzhou dedicated to hadron cancer therapy has been designed and is under constructing in Lanzhou by IMP staff. For the complementarity of proton and carbon ions in the performance of cancer therapy, HITFiL is designed to accommodate both proton and carbon ions. It is mainly composed of two ECR ion sources for beam shift, a Sector Focusing Cyclotron, a MEBT, a synchrotron, a HEBT and four treatment terminals. H<sub>2</sub><sup>+</sup> or C<sup>5+</sup> beam produced by ECR source is pre-accelerated by the cyclotron to 7 MeV/u, and then stripped to H<sup>+</sup> or C<sup>6+</sup>

before the synchrotron injection point [14]. For the compactness, easy operation and maintenance, all permanent magnet ECR ion source is the best option for the complex's ion source choice.

For the project,  $100\mu\text{A C}^{5+}$  is desired for routine operation, therefore, the ion source should be capable of delivering more than  $120\mu\text{A C}^{5+}$  during source commissioning. Since  $\text{C}^{5+}$  is a comparably high charge state ion, especially in terms of the high beam intensity desired, very good plasma confinement must be provided by the permanent magnets. This ion source LAPECR3 has been designed and successfully built at IMP. As shown in Fig. 4, the ion source's magnet is mainly composed of the injection magnetic rings, extraction magnetic rings, middle magnetic ring and the 24-segmented Halbach structure hexapole magnet. An iron plug has been employed to boost the injection magnetic field peak to  $\sim 1.8\text{ T}$  which is essential for the high B mode operation for an ECR ion source at  $14.5\text{ GHz}$ . Fig. 5 is the axial field distribution. The magnet design tricks utilized on LAPECR2 ion source have also been applied on LAPECR3, i.e. the hexapole magnet end toward the source extraction side has been designed with a conical shape to refine the total magnetic field configuration, and one of the extraction magnetic rings has been shaped to fit the hexapole magnet accordingly. The plasma chamber is originally designed with the ID of  $\varnothing 50\text{mm}$ , which accordingly has the magnetic field of  $1.14\text{ T}$  at the chamber inner wall. The glue problem eventually resulted in the shrinking-down of the hexapole magnet inner bore size. According to the magnetic field measurement, only  $\sim 1.0\text{ T}$  field strength has been obtained at the  $\varnothing 47.5\text{ mm}$  ID plasma chamber inner wall. Table 4 gives the final key parameters of the ion source in comparison with the designed ones.

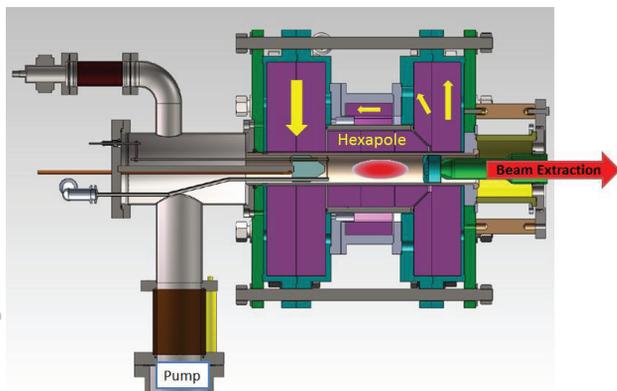


Figure 4: Sectional plot of the LAPECR3 ion source.

But to produce intense  $\text{C}^{5+}$  beam is still challengeable. The ionization potential of  $\text{C}^{5+}$  is  $\sim 400\text{ eV}$ , therefore, electron energy up to  $1\text{ keV}$  is required to be optimum for the ion production. High microwave power heating and good plasma confinement are the necessities for the production of high charge state ions. However, the material feeding is a big issue. Since pure carbon normally exists in a solid state that needs a very high temperature to evaporate which is not applicable with ECR ion source in terms of reliability, especially for the

cancer therapy purpose that needs a long-term stability of the ion beam. Gas feeding is so far the best solution. Carbon compound gas such as  $\text{CO}_2$ ,  $\text{CO}$ ,  $\text{CH}_4$ ,  $\text{C}_2\text{H}_2$ ,  $\text{C}_3\text{H}_8$  and etc. have been already tried in many labs to produce intense carbon ion beams, and the work in NIRS has a more detailed investigation on the issues how to produce intense high charge state carbon ion beams, the gas choice and some other techniques [15]. Having in mind that the machine is going to be used as a turnkey device for cancer therapy treatment, cheap and easy handling gas such as  $\text{CH}_4$  and  $\text{C}_2\text{H}_2$  will be used as the feeding gas. Isotope gases can be used in study but not in this application. The ion source is already assembled and installed on the test bench. Once the beam line parts are connected, source conditioning will be started.

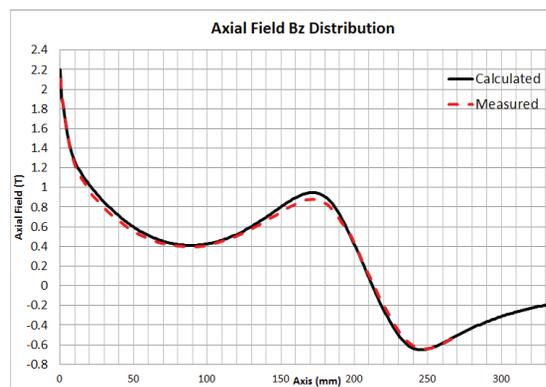


Figure 5: Axial magnetic field distribution (measured and designed results) of LAPECR3 source.

Table 4: Main Parameters of LAPECR3 Source

Parameters	Designed	Final specs.
Axial Field ( T )	1.8-0.40-0.94	1.8-0.40-0.89
Field on Inner Chamber Wall -Br ( T )	1.14	1.0
Mirror Length ( mm )	170	172
ECR Length ( mm )	64	$\sim 70$
$f$ ( GHz )	13.75-14.5	13.75-14.5
Chamber ID ( mm )	50	47.5
Effective Chamber Volume ( L )	0.33	0.30
Max. Designed Operation HV ( kV )	25	28
Max. Designed $\mu\text{W}$ Power ( kW )	0.70	0.70
Dimension ( mm )	$\varnothing 450 \times 380$	$\varnothing 455 \times 382$
NdFeB Weight (kg)	157	157
NdFeB Type	N50M	N50M

## CONCLUSION

Three different design all permanent magnet ECR ion sources have been designed and built at IMP for multi-purposes. LAPECR1 source is now used as the HIRFL accelerator preinjector to deliver  $H^+$  or  $H_2^+$  beams. LAPECR2 source has been used on the 320 kV multi-disciplinary HV platform for 6 years. The ion source has produced different ion beams of 18 elements for the successive 5 experimental terminals for more than 30,000 beam hours. The latest built LAPECR3 source will be commissioned soon and once it is done, it will be removed and connected to the HITFiL complex to deliver intense  $H_2^+$  or  $C^{5+}$  beams.

## REFERENCES

- [1] K. Halbach, Nucl. Instrum. Methods 169 (1980) 1.
- [2] D. Leitner, C. M. Lyneis, T. Loew, D. S. Todd, S. Virostek, and O. Tarvainen, Rev. Sci. Instr. 77 (2006) 03A302.
- [3] H. W. Zhao, et al., Rev. Sci. Instr. 83 (2012) 02A320.
- [4] Tetsuro Kurita, et al., Nucl. Instr. and Meth. B 192 (2002) 429.
- [5] T. Thuillier, T Lamy, L. Latrasse and J. Angot, Rev. Sci. Instr. 79 (2008) 02A330.
- [6] Z. Q. Xie, Rev. Sci. Instrum., 69 (1998) 625.
- [7] D. Hitz, et al., Rev. Sci. Instr. 75 (2004) 1403.
- [8] P. Sortais, et al., "Development of Compact Permanent ECRIS", Proceedings of 12<sup>th</sup> International Workshop on ECR Ion Sources, Tokyo, April 1996, p.44 (1995).
- [9] Dan Z. Xie, Rev. Sci. Instrum. 73 (2002) 531.
- [10] B. Jacquot and M. Pontonnier, "The New 10 GHz Caprice Source-Magnetic Structures and Performances", Proceedings of 10<sup>th</sup> International Workshop on ECR Ion Sources, Report ORNL CONF-9011136, p.133 (1990).
- [11] H. W. Zhao, B. W. Wei, Z. W. Liu, Y. F. Wang, W. J. Zhao, Rev. Sci. Instr. 71 (2000) 646.
- [12] L. T. Sun, et al., Nucl. Instr. and Meth. B, 263 (2007) 503.
- [13] X. Ma, et al., Journal of Physics: Conference Series 163 (2009) 012104.
- [14] Weiping Chai, Jiawen Xia, Jiancheng Yang, Youjin Yuan, Mingtao Song, Bing Wang, Jian Shi, Peng Li, "Study of Charge Exchange Injection in HITFiL", IPAC'11, San Sebastián, September 2011, THPS044, p. 3520 (2011); <http://www.JACoW.org>
- [15] A. G. Drentje, A. Kitagawa, and M. Muramatsu, Trans. Plasma Sci. 36 (2008) 1502.