LATEST TRENDS IN ECR TECHNOLOGY AND PANTECHNIK ECRIS

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Abstract

Electron Cyclotron Resonance Ion Sources are used worldwide in research domains, which need high intensity and/or high charge state beams. The reliability and reproducibility of beams provided by these sources allowed using for heath care, in particular for Hadrontherapy of Cancer. Pantechnik, world leader in industrial ECRIS, provides different models of these sources, allowing use for research, therapy and surface characterization.

INTRODUCTION

The advent of Electron Cyclotron Resonance Ion Sources 3(ECRIS) in Nuclear Physics, Particle Science, Surface and Atomic Physics has placed an important milestone on the history of the development of new Heavy-Ion beams with high energy and high intensity [1]. Firstly, ECRIS have upmost ionization efficiency, mainly if one considers gaseous elements. Secondly, ECRIS are virtually chemical independent; i.e. any element can be ionized. Finally, these sources can ionize elements to high charge states, which gives access to the “new physics” of highly charged states at “zero” beam energy whilst this is an important ingredient for producing accelerated beams in a wide range of energies. In this contribution, I will introduce present trends in Electron Cyclotron Resonance Ion Source technology and show latest Pantechnik ECRIS developments.

LEARINING FROM GELLER

A performing ECRIS can be conceived respecting the known recommendations given by R. Geller [1]:

1) The better the confinement, the higher will be the ionisation efficiency and the production of higher charge states. In order to achieve a better confinement, radial magnetic mirrors, in addition to axial mirrors should be built in the ECRIS. This concept is called "minimum B structure", having a minimum magnetic field in the centre of the cavity (see figure 1).

2) The mirror ratio should be of the order of $B_{max}/B_{min} \approx 2$.

3) In addition, a ratio of $B_{max}/B_{ECR} >> 1.5$ is recommended, where by B_{ECR} is given by:

$$B_{ECR} = m_e w / e \qquad (1)$$

where m_e and e are respectively the electron mass and charge and $w = 2\pi f$, being f the resonance frequency.

4) A weaker mirror near the extraction will increase ion leaks in this region with respect to the injection side, therefore enhancing the performances of the ECRIS.

Some comments can be added to the recommendations of R. Geller. The radial magnetic field can be hexapolar, octupolar or even dodecapolar. ECRIS with such radial magnetic confinements works properly. The quadrupole configuration is not likely due to its very narrow radial extension.

The higher the plasma density, the higher will be the mean charge of the plasma, therefore allowing higher charge states for the extracted beams. Higher density is achieved enhancing the magnetic field and the Radio Frequency (RF) injected in the ECRIS. Examples of magnetic fields and Radio Frequencies for high performance ECRIS are given in Table 1. The recommended values correspond to the maximum radial magnetic field in the wall of the plasma chamber and in the injection side of the source. Usually, the extraction magnetic field is equivalent to the radial field.

In order to deliver high beam currents, the ECRIS needs high-magnetised plasma volume, which implies in large volume chambers. The magnetic field structure can be achieved using permanent magnets or coils, which can be superconducting or not. Latest developments of Nd-Fe-B permanent magnets with very high remanence together with good coercivity were extremely important in ECRIS development, allowing reaching magnetic strengths and reliability at high RF frequency. Permanent magnets also allows having high performance ECRIS with a minimum electrical power. Moreover, the use of Superconducting coils opened up the possibility of reaching even higher charge states. This technique is presently extremely reliable for reaching high fields in the axial direction, allowing using frequencies of 18GHz. Additional radial multipole superconducting structures allows working at even higher RF frequencies: 24-28GHz and reaching even higher charge states.

Table 1: RF frequencies and magnetic fields for ECRIS

RF frequency (GHz)	**B resonance (T)**	**B radial (T) - recommended**	**B max (T) - recommended**
6.0	0.214	0.43	0.64
10.0	0.357	0.71	1.10
14.5	0.518	1.04	1.55
18.0	0.643	1.28	1.93
24	0.857	1.72	2.57
28	1.0	2.0	3.0
56	2.0	4.0	6.0

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2.45 GHZ ECRIS FOR HIGH INTENSITY BEAMS

High intensity monocharged beams can also be produced by ECR ion sources with different magnetic configuration [2]. These sources are also commonly called microwave.

The frequency of these sources is significantly smaller – 2.45 GHz – than the ones used for multiple charged states. This important difference is due to two main reasons:

1) producing mono-charged states (1+) ions need less energetic electrons
2) emittance of the extracted beams are strongly dependent on the magnetic field in the extraction region: lower magnetic field (corresponding to lower frequency) gives smaller emittance.

The emittance is a very important parameter when transporting the ion beams, in particular for very high intensities. The divergence (x') of the extracted beam can be, in first approximation, calculated by the relation (2):

$$x' = \frac{1}{2}\frac{qmwr}{ep} \qquad (2)$$

where q, m and p correspond to the charge, mass and momentum of the extracted beam and r is the radius of the plasma aperture.

Intensities exceeding 10 mA, up to about 100 mA can be produced and extracted from this kind of sources, provided special care is taken in the extraction zone. The source SILHI conceived at CEA-Saclay is an example of this kind of ion source [3]. In particular, a multi-electrode extraction constituted by 5 different electrodes was developed. Intensities exceeding 100 mA can be produced and transported.

PERMANENT MAGNET ECRIS

Permanent magnet ECRIS are usually very compact and can be used for production of low, moderate and relatively high charge states. Moreover, mono-charged ion source, like SILHI, can be, alternatively, built with permanent magnets or coils, depending on the use.

Pantechnik, which is the world leader in industrial ECRIS, has an extended catalogue of full permanent magnet ECRIS. The sizes and variety of the sources are listed in the Table 2.

Please, note that the sources listed in the table can produce any ion, provided atom injection is provided. Condensable elements are usually produced using internal ovens or the sputtering technique, where ions from the ECR plasma hit a sample of the element to be ionized. The beams of H, He, C and Ar are examples for giving the order of magnitude of the beams produced by each ECRIS.

Table 2: Pantechnik full permanent Magnet ECRIS

Source	**f (GHz)**	**P(W)**	**W(kg)**	**Intensities - examples**
Monogan M-100	2.45	30	0.3	H+: 100µA He+: 100µA Ar+: 50µA
Monogan M-1000	2.45	1200	15	H+: 30mA He+: 20mA Ar+: 10mA
Nanogan	10	100	11	He+: 1mA Ar8+: 20µA
Nanogan-14.5	14.5	200	40	He2+: 200µA Ar8+: 60µA
Supernanogan	14.5	6000	200	He2+: 1mA C4+: 200µA Ar8+: 200µA

These sources are used for research in Surface, Atomic, Nuclear Physics, ion implantation and as injectors for particle accelerators. Particularly in India and with the collaboration of GEEBEE International [4] one Nanogan ECRIS is running at IUAC, New Delhi, one Supernanogan in TIFR, Mumbai and a new Nanogan-14.5 will be soon installed in IOP, Bhubaneswar.

Recently, Supernanogan is being used as injector for cancer treatment via Hadrontherapy (see Figure 1). The advantage of Hadrontherapy compared with other radiation techniques for cancer treatment is the ballistic effect of ions due to the Bragg peak and low straggling. The energy deposition is mainly located in the end of the ion path, keeping healthy tissue safe of irradiation. This is not the case of photons or neutrons.

ECRIS permits producing reliably different ion beams within short commuting time. Therefore, Supernanogan is being used for producing 200 µA of C (4+) and 1.0 mA of H_3 (+) for Hadrontherapy [5]. These two beams have the same A/q ratio and, as a consequence, can be accelerated by the same RFQ (radio-frequency quadrupole structure) at the same acceleration voltage.

Specially for Hadrontherapy centers, but not exclusively, Pantechnik developed a gas injection technique based on Mass-flow controllers [6], which allows unprecedented stability and reproducibility of the produced beam. These beams are stable at the level of +/- 2.5% during several days, reducing operator intervention to a minimum.

The Heidelberg Ion Therapy (HIT) centre in Germany is treating about 1,000 cancer patients per year since 2009 using two Supernanogan ECRIS. Other centres for Hadrontherapy using Supernanogan are located at

Marburg and Kiel in Germany and Pavia in Italy. A different ECRIS at lower frequency is also used in Japan for Carbon therapy in Chiba and Hoyogo.

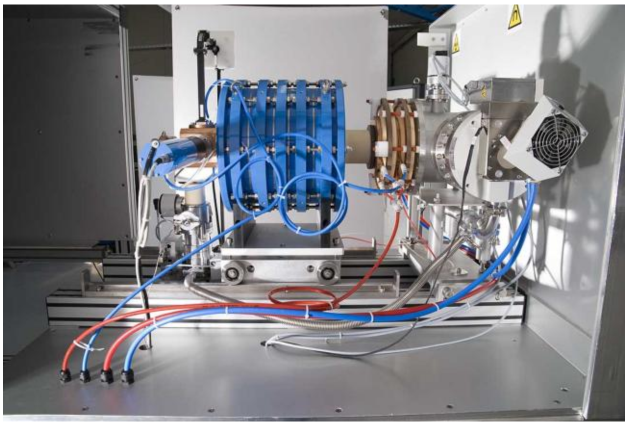

Figure 1: Hadrontherapy bench with Supernanogan full permanent magnet ECRIS.

18 GHZ AND HIGHER FREQUENCY ECRIS

18GHz ECRIS provides intense beams of high charge states using magnetic fields, which can still remain in the domain of permanent magnets, at least for the radial magnetic circuit. According to the recommendations listed in the Table 1, the axial magnetic field is already outside the domain of pure permanent magnets. The use of coils is mandatory, being the choice between room temperature copper or superconducting HTS (High Temperature) or LTS (Low Temperature) coils.

PANTECHNIK has developed and improved its family of ECRIS in collaboration with research laboratories like GANIL and LPSC in France and IUAC in India. From this collaboration, the first ECRIS using He-free High Temperature Superconducting wire technology (HTS) was born in 2002: PK-DELIS.

The goals of that development were to reduce the power consumption of the coils from 200 kW to 15 kW, for avoiding liquid He in the superconducting coils and to demonstrate the feasibility of such hybrid HTS - permanent magnet (for the radial magnetic field) source. PK-DELIS works since then successfully at New Delhi.

The new source of Pantechnik is conceived for reaching optimum performances at 18 GHz RF frequencies. Moving to this direction, PK-ISIS, our new source, has much higher axial and radial magnetic fields (2.1 T axial B_{inj} and 1.32 T radial field in the wall), a larger plasma volume, variable B_{min} via an independent coil and a large and opened extraction region. Moreover, PK-ISIS integrates modern design concepts, like RF direct injection (2.5 kW availability), DC-bias moving disk, out-of-axis oven and axial sputtering facility for metal beams. PK-ISIS delivers 5 to 10 times more beam intensity than the original PK-DELIS and/or shifting the charge state distribution to higher values.

PK-ISIS is built with Low Temperature Superconducting wire technology (LTS), but keeps the He-free concept, extremely important for a reliable and easy operation. The radial field circuit is permanent magnet made. Finally, PK-ISIS is also conceived for using in a High-Voltage platform with minor power consumption.

The main parameters of the PK-ISIS source are listed in the Table 3.

Table 3: Main parameters of PK-ISIS ECRIS

Item	**Description / value**
$B_{injection}$	Variable < 2.1 T
$B_{extraction}$	Variable < 1.5 T
$B_{minimum}$	Variable 0.4 T < B < 0.6 T
$B_{radial-wall}$	1.32 T
Frequency	18 GHz
RF power	2.5 kW available
Chamber diameter	82 mm
Chamber lenght	450 mm
Yoke diameter	680 mm
Yoke lenght	730 mm
Weight	1,500 kg
Insulation	30 kV
Cryogenics	4.2 K Pulse Tube Cryocooler
Cryogenics Power	1 W – Cryogenic free
Neutral input	Gas, Oven (<1400° C), Sputtering

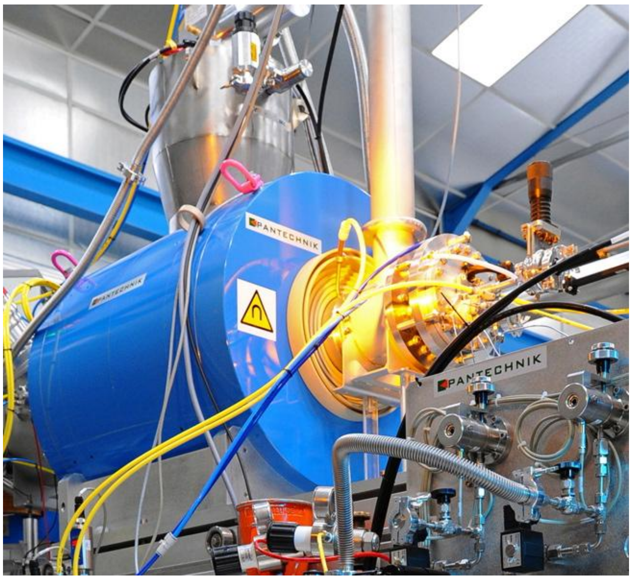

Figure 2: PK-ISIS ECRIS

The intensities already obtained by PK-ISIS are listed in the Table 3 below. Please, note that these values were obtained during commissioning in the Pantechnik premises. The intensities – mainly for metallic beams – should be taken as lower limits.

Table 3: Beam intensities measured with PK-ISIS

Ion	**Intensity (μA – electrical)**
^{4}He (2+)	2,400
^{13}C (4+)	>500
^{13}C (6+)	50
^{14}N (5+)	>1,000
^{16}O (6+)	1,500
^{16}O (7+)	230
^{40}Ar (12+)	200
^{40}Ar (14+)	100
^{84}Kr (17+)	100
^{129}Xe (26+)	100
^{181}Ta (26+)	20
^{181}Ta (30+)	13
^{181}Ta (32+)	6
^{209}Bi (29+)	35
^{209}Bi (31+)	25
^{209}Bi (33+)	15

Best performances of ECRIS are obtained with full Superconducting (axial and radial) sources, like VENUS [7] developed at LBNL, Berkeley, USA and SECRAL [8] developed at IMP, Lanzhou, China. These two sources work at 28 GHz and 24 GHz respectively. Beam intensities up to 2,8 mA of ^{16}O (6+) and of the order of 850 μA of ^{40}Ar (12+) can be obtained. However, we should note that the technology of having hexapolar high magnetic field coil structure inside a set of solenoid coils, or the inverse, is extremely critical from the mechanical point of view. These sources are presently close to the limits of this technology.

NEW TRENDS AND DEVELOPMENTS

New generation ECRIS are being presently studied focusing higher and higher frequencies, with subsequent higher magnetic fields. New studies are being done at LBNL concerning ECRIS of frequencies as higher as 56 GHz using Nb_3Sn technology for the superconducting coils [9].

However, it should be noted that the design of such magnetic structures including multipoles inside solenoid fields is challenging, mainly when superconduting coils are used. This difficulty is also enhanced by the high X-ray flux that superconducting coils are subject. New structures and solutions should be, therefore, developed in this case.

Pantechnik together with GANIL are presently developing a new magnetic structure in order to overcome these limitations [10]. This totally new design incorporates a symmetry, which allows radial and axial confinement without the use of multipoles. The first source for multiple-charged ions using this new design is being built at Pantechnik and will be tested in 2011.

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