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CHALLENGES AND PROSPECTS OF ELECTRON CYCLOTRON RESONANCE CHARGE BREEDERS

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Abstract

Electron cyclotron resonance charge breeder (ECR CB) is one of the instruments used to boost the radioactive ion beam (RIB) charge state in isotope separator on-line (ISOL) facilities. While the ECR CB can manage intense 1+ RIB without difficulty, the present CB generation co extracts significant amounts of impurities which can be detrimental to the study of very low intensity N+ RIB in today facilities if no downstream high mass resolution separation is available. This work investigates the improvements achievable with a new generation 18 GHz ECR CB applicable to future facility like EURISOL. The study shows that with a modified ion source geometry, an optimized magnetic confinement, a careful wall metal choice like beryllium, a UHV vacuum technology, the charge breeder performance will improve as follows: 20 % higher capture efficiency, -40% charge breeding time, charge state ion production with mass over charge of 3 up to xenon and over 6 up to uranium, co-extracted contaminant density reduction by a factor 60 to 600. An 18 GHz ECR CB ion source layout is finally proposed for EURISOL.

STATUS OF ECR CHARGE BREEDING

Ion source charge breeders are used in Isotope Separation Online (ISOL) facilities to boost the 1+ radioactive ion beam (RIB) charge state produced by target ion source (TIS) to N+ high charge state. The RIB beam is next filtered by a mass separator and finally injected into a post accelerator. Figure 1 presents the layout of such ISOL installation. Among the numerous key parameters of ISOL facilities, one can cite the:

- reliability and selectivity of the TIS,
- quality of the 1+ RIB purification,
- charge breeding time,
- charge breeding efficiency and
- achievable ion charge state of the charge breeder,
- downstream mass separation of the N+ RIB after the ion source CB.

Two types of charge breeders applicable to ISOL have been developed: the electron beam ion source charge breeder [1] (EBIS CB) and the electron cyclotron resonance ion source charge breeders (ECR CB)[2]. Table 1 presents the majors characteristics of the two ions sources type. Experiments done at CERN and later on both technologies concluded that EBIS CB and ECR CB are complementary[3]. Recently, the ECR CB installed at the CARIBU facility (Argonne National Laboratory, ANL) was stopped and replaced by an EBIS CB[4]. The origin of this decision is as follows. The 1+ RIB signal intensity of CARIBU was in the range 10^2-10^4/s, lower than expected. The downstream mass resolution after the CB was M/ΔM~300, resulting in a large N+ RIB signal contamination > 97%. The downstream linear accelerator could not purify further the RIB and experiments were eventually not possible.

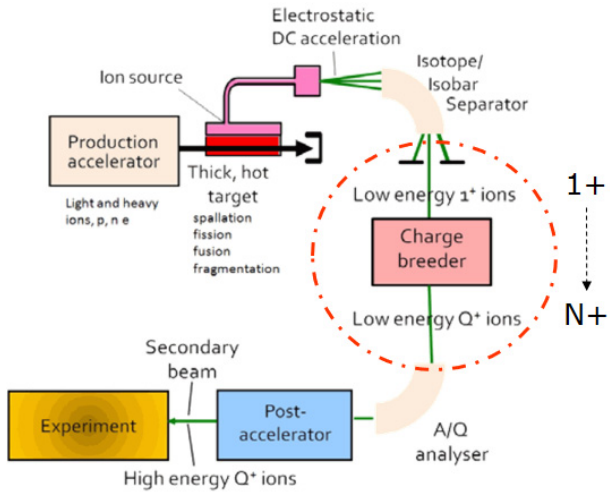

Figure 1: Layout of isotope online (ISOL) accelerator.

Table 1: Today EBIS and 14 GHz ECRIS CB Features.

	EBIS CB	today ECRIS CB
Max. 1^+ RIB intensity	$<10^{10}$/s	$>10^{14}$/s
CB time to N+ (ms)	10-100	100-300
robustness	medium	High
1+N+ conversion efficiency	25%	5-20%
Operation mode	pulsed	CW or pulsed
RIB total contamination rate extracted	~10^5 /s	~10^9-10^{10}/s
Downstream mass resolution $M/\Delta M$	~300	≥ 1000
Upstream requirement	Ion cooling	None
Highest charge state	Bare ions	A/Q=3→A~60 A/Q=7→A~150

The same situation with low RIB intensity and low downstream mass separation condition also exists at the TRIAC facility (TRIUMF, Canada), but possibilities to purify the beam after the linac with thin strippers save some

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experiments[5]. There, an EBIS CB will be installed to complement the ECR CB[5]. More recently, SPIRAL1 facility (GANIL) was upgraded with a PHOENIX CB. Thanks to the RIB post-acceleration in the CIME cyclotron, a very high mass separation M/ΔM~10000 is expected [6] granting an efficient cleaning of the N+ RIB signal, making it suitable for final RIB experiments. The SPES facility (LNS), under construction, is also equipped with a medium mass separator M/ΔM~1000[7]. With a RIB signal intensity of 10^6/s and specific background reduction in the ECR CB, a clean N+ RIB signal is also expected.

POSSIBLE ECR CB UPGRADE

Ion Capture

Experimental data, confirmed by calculation and simulation, shows that the 1+ beam capture in existing 14 GHz ECR CB is not optimized: nearly 20% of the incoming ions are ionized on flight to 2+, 3+ and 4+ while crossing the plasma but are not trapped.[8] These ions are directly extracted and are then lost as N+ signals. Figure 2 presents the plasma length required to capture 99% of the 1+ signal as a function of the ECR frequency. One can see that at 14 GHz, a booster with the present measured plasma density [8] would require a 40 cm long plasma to grant a high cap-ture efficiency, while the existing CB plasma is ~14 cm (red cross). Because the plasma density is proportional to the ECR frequency to the square ($n_p \sim f_{ECR}^2$), an 18 and 28 GHz ECR CB would need 25 cm and 10 cm plasma length respectively to capture all the 1+ beam.

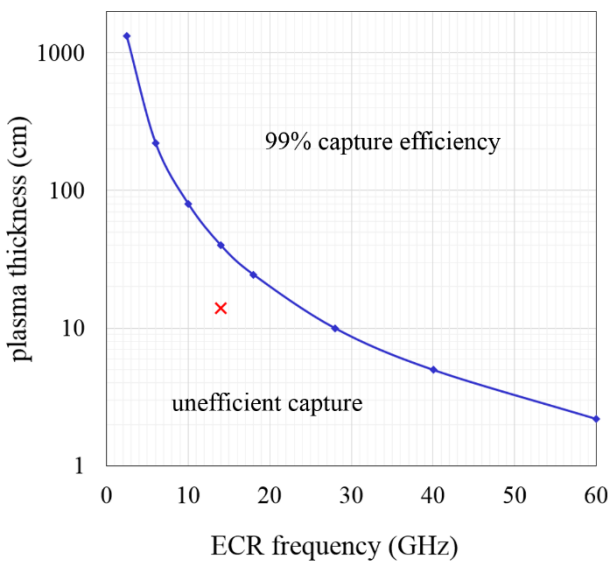

Figure 2: Plasma length required to capture efficiently an incoming 1+ beam as a function of the ECR frequency in an ECR CB (blue line). The existing PHOENIX Booster plasma is located by a red cross.

Charge Breeding Time

Another promising feature of the ECR frequency scaling ($n_p \sim f_{ECR}^2$) is the associated reduction of the charge breeding time τ_{CB} since $\tau_{CB} \propto 1/n_p$. As an illustration, Figure 3 shows how fast the charge breeding time theoretically decreases with the ECR frequency. Table 2 gives an example for the ECR frequency effect on $^{35}K^{10+}$ CB time.

Table 2: Theoretical evolution of the charge breeding time for $^{39}K^{10+}$ as a function of the ECR frequency, using 14 GHz data as a reference. The subsequent effect on material sputtering from the wall is indicated for convenience.

f_{ECR} [GHz]	τ_{CB} [ms]	Relative τ_{CB}	Relative density of contaminants
2.45	262	32	0.03
14	82	1	1
18	33	0.60	1.65
28	21	0.25	4

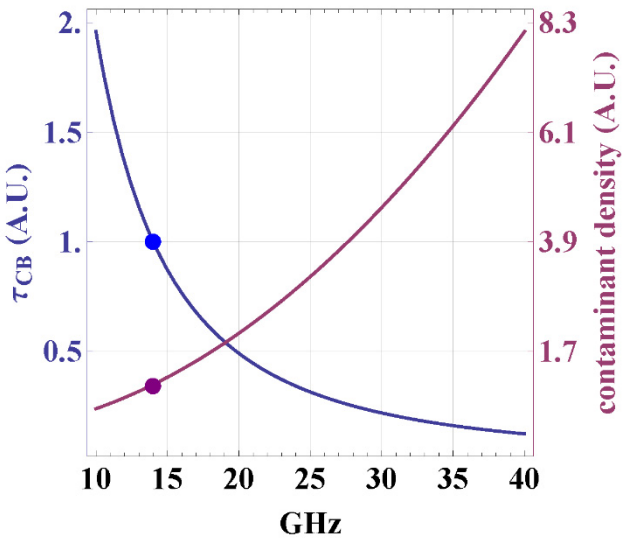

Figure 3: Blue curve, left axis, relative evolution of the charge breeding time as a function of the ECR frequency. The blue point is today 14 GHz ECR CB reference. Purple curve, right axis, concomitant evolution of the contaminant density in the plasma.

On the other hand, when the ECR frequency is increased, the sputtered materials from the walls follow the plasma density, leading to a higher contaminant density in the plasma for a given ECR plasma volume (see Figure 3). Mitigating such an increase of contaminant density would require a high downstream mass resolution $M/\Delta M$~10000 and also other source of background reduction as discussed in the next section.

Background Reduction by Volume Effect

A way to reduce significantly the contaminant density is to increase the plasma chamber dimension. The reason for this effect is as follows. The contaminant flux Φ from the wall is proportional to the plasma chamber cylindrical surface (with radius r and length L):

$$\Phi \propto 2\pi r L + 2\pi r^2 \quad (1)$$

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While the ECR plasma volume V_{ECR} is proportional to the cylinder volume:

$$V_{ECR} \propto \pi r^2 L \tag{2}$$

Leading to a contaminant density C:

$$C \propto \frac{\Phi}{V_{ECR}} \propto \frac{2}{r} + \frac{2}{L} \tag{3}$$

Figure 4 shows how the ECR CB geometry can be optimized to reduce the contaminant density in the plasma. For instance, a plasma chamber with a 10 cm radius and a 80 cm length would divide the contaminant density by a factor of 4 with respect to the existing booster. Such a geometry would compensate the increase of contaminant yield due to a 28 GHz ECR frequency (see table 2).

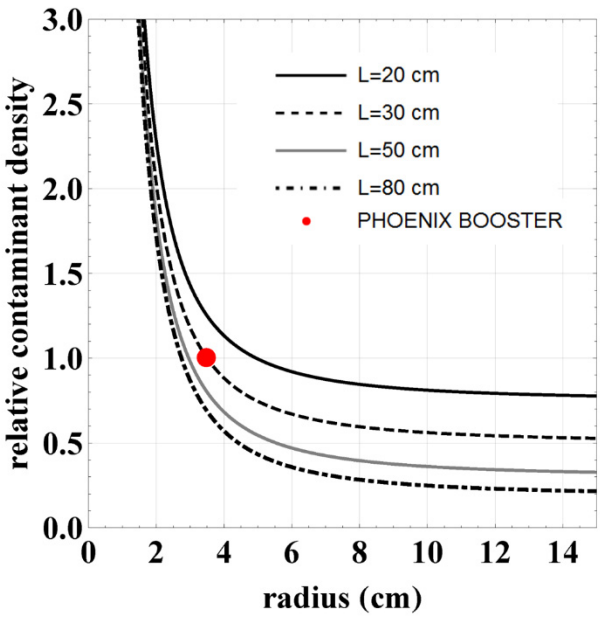

Figure 4: relative contaminant density evolution versus the plasma chamber cylinder radius for various plasma chamber length. The existing PHOENIX ECR CB geometry is indicated with a red dot.

Background Reduction by Wall Material Optimization

A careful ion spectrum analysis of contaminants shows that it is first composed of the chemical species included in the wall metal alloy and second with other elements present as traces in the ore used to build the metal. Further compli-cation comes from the presence of natural isotopes for each element. Since ECR CB generates multi-ionized ions, the resulting mass over charge ion spectrum includes a very large number of peaks with various intensities. The difficulty for ISOL facility using ECR CB with low downstream mass separation is to find a RIB mass over charge ratio suitable for post-acceleration where the local mass contamination is low. Because high mass elements have more electrons than light ones, the use of material containing heavy masses like stainless steel must be avoided as plasma chamber metal. Several laboratories performed research and development to investigate, reduce or redistribute the contamination sputtered from the plasma chamber wall. LPSC shown that an unstable plasma multiplies by 10 the atom sputtering rate from the walls[9]. KEK converted the material exposed to the plasma to Al [10], while Argonne and TRIUMF laboratories extended the use of this material to ion injection and extraction areas [5,11,12]. Aluminum features interesting advantages for ECR plasma as it is a light metal with a few electrons, it has no stable isotope and the secondary electron emission from the aluminum oxide layer naturally covering the metal surface boosts the electron density. The aluminum deposition at TRIUMF helped reducing background at specific places in the ion spectrum allowing post-acceleration of RIB[5]. ANL will test in a near future conformal coating by atomic layer deposition (ALD) technique [13]. ALD enables to deposit a thick homogeneous Al2O3 layer in the ion source. The drawback with layer deposition is that it degrades with time and there is no warranty to keep the contamination level from one layer deposition to another. SPES team has planned to test liners made of monoisotopic materials (Nb,Ta,W) in collaboration with LPSC[14]. Pure aluminum is a soft material with poor mechanical properties and it is unfortunately not possible to machine a whole ECR CB plasma chamber with it. A set of two new materials are proposed in this study to build a plasma chamber: beryllium and AlBeMet©. Beryllium is a very light monoisotopic metal with a melting temperature of 1287°C and high mechanical properties suitable to machine a whole plasma chamber. AlBeMet© is a mixture of aluminium and beryllium which allies the good thermal conductivity of aluminium and the good mechanical properties of beryllium. Figure 4 presents the simulated contaminant spectrum of stainless steel (excluding extra element contamination coming with the stainless steel compounds) and pure beryllium (including all possible trace contaminants). One can see that the beryllium spectrum concentrates the impurities on Be peaks (A/Q=4.5, 3 here) and the impurity intensities are a factor 10^2 to 10^5 lower elsewhere.

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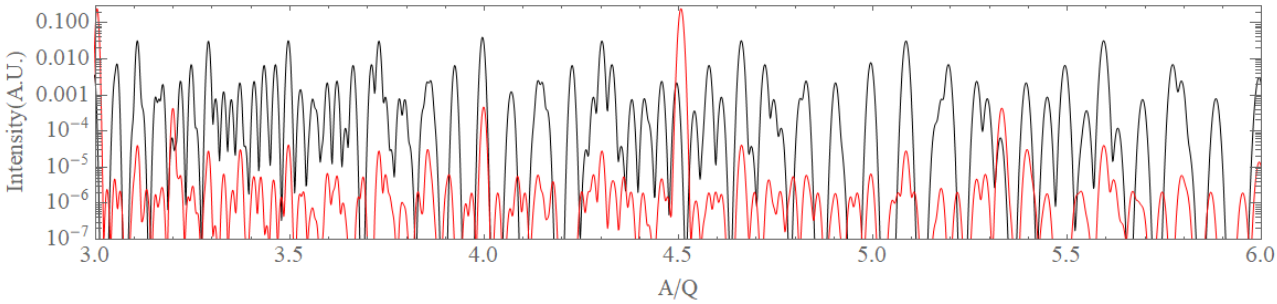

Figure 5: Ion Mass spectrum simulated for stainless steel (black) and pure beryllium (red) plasma chamber.

Gas Background Reduction

Today ECR CB are based on 20 years old technology including plastic o-rings and no bake able assemblies. The base vacuum in the ion source is of the order of 10^{-6} to 10^{-8} hPa at best. The probability of gas ionization being very high in an ECR plasma, a high gas contamination yield comes with the N+ RIB of interest. The contaminants come either from the permeation through o-rings or by the buffer gas injection system used to sustain the ECR plasma. Both source of gas contaminant can be efficiently reduced as follows. A careful new ion source design using ultra high vacuum (UHV) technology and an online system to bake the plasma chamber and the surrounding vacuum chambers up to 300°C would give a base vacuum in the range 10^{-9} to 10^{-10} hPa. A special care must also be taken to the buffer gas injection where a gas purity of 99.999% still brings a large amount of impurities. When limiting buffer gas to H_2 and He, it becomes possible to purify online the injected helped with a 4K cryopump. Completed with a fully bake able gas injection system, the gas contamination from the buffer gas injection will decrease significantly by several order of magnitude at least. Such a clean gas injection system has been successfully implemented on the CARIBU gas catcher at ANL.[15]

High Charge State Improvement

The ECR ion source know how improved a lot since twenty year. Today high efficiency and highly otimized ECR ion sources can produce Xe^{42+} (A/Q~3) and U^{42+} (A/Q~6) on a daily basis.[16,17]. The key for such improvement are an optimized magnetic confinement [18] and a large plasma chamber radius[16,17,19]. When increasing the plasma chamber radius, the ion confinement time is mechanically increased and it can be argued that the CB time should increase which can be detrimental for an efficient N+RIB post acceleration. But the CB time can also be reduced by adapting the extraction magnetic field intensity which controls the ion extraction. So a flexible ion magnetic confinement produced by hexapole coils and a set of axial solenoids would allow to adapt the ion confinement time and charge state to a specific RIB element.

PROSPECT WITH A NEW GENERATION ECR CHARGE BREEDER FOR EURISOL

The last section demonstrates that there is a clear interest to develop a new generation ECR CB. Table 3 summarizes the possible set of improvements of ECR CB as a function of the ECR frequency. Depending on the physics needed, a 28 GHz ECR CB can be considered if an important CB time reduction is expected (-75%), the condensable contaminant reduction could reach a factor 20-200 and the gas contaminant a factor 1000 with respect to today ECR CB operated at 14 GHz with a stainless steel plasma chamber. In this case a downstream high mass resolution of ~10000 is mandatory, along with a RIB signal > 10^5-10^6 pps. Another possibility is to choose an 18 GHz upgraded ECR CB which would reduce the CB time by -40% and offer a condensable and gas background reduction in the range ~60-600 and 1000 respectively. The wide know-how on 18 GHz ECRIS would make this latter choice very safe as far as the magnetic field operation safety and ion source performance are concerned.

Table 3: Possible Booster improvements vs ECR frequency. The existing 14 GHz booster being considered as a reference.

f_{ECR} [GHz]	14	18	28
1+/N+ RIB efficiency	+20%	+20%	+20%
Relative τ_{CB}	0%	-40%	-75%
Higher N+ charge state	+20%	+20%	+20%
sputtered contaminant density in plasma	-80%	-67%	-20%
Gas contaminant density	÷ 1000	÷ 1000	÷ 1000
ion spectrum sputtered contamination	÷ 100 ÷ 1000	÷ 60 ÷ 600	÷ 25 ÷ 250

Figure 6 proposes the layout of a new generation 14-18 GHz ECR CB suitable for a facility like EURISOL. The magnetic field is generated by a set of 8 NbTi superconducting coils. Two large coils are present at each end to pilot the injection and extraction peak field, while 6 smaller coils located in between control the axial magnetic field profile. This results in the possibility to generate very flexible axial magnetic profile, including flat field geometry [20,21], or even two consecutive closed ECR zones. Very long ECR plasma zone can be created up to 500 mm for 14 GHz or 450 mm for 18 GHz. Such a long ECR zone will grant an optimum RIB capture efficiency. Typical axial magnetic field mirrors are displayed in Figure 7. The grey plot indicates a 400 mm long 14 GHz ECR zone, while the black plot shows a 330 mm long 18 GHz ECR zone. The

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radial confinement is done with an NbTi hexapole delivering up to 1.4 T at the plasma chamber wall. The possibility to control independently the radial and axial magnetic fields will enable to control the ion confinement time and thus find more easily ion source tuning providing short CB time and/or high charge state beams.

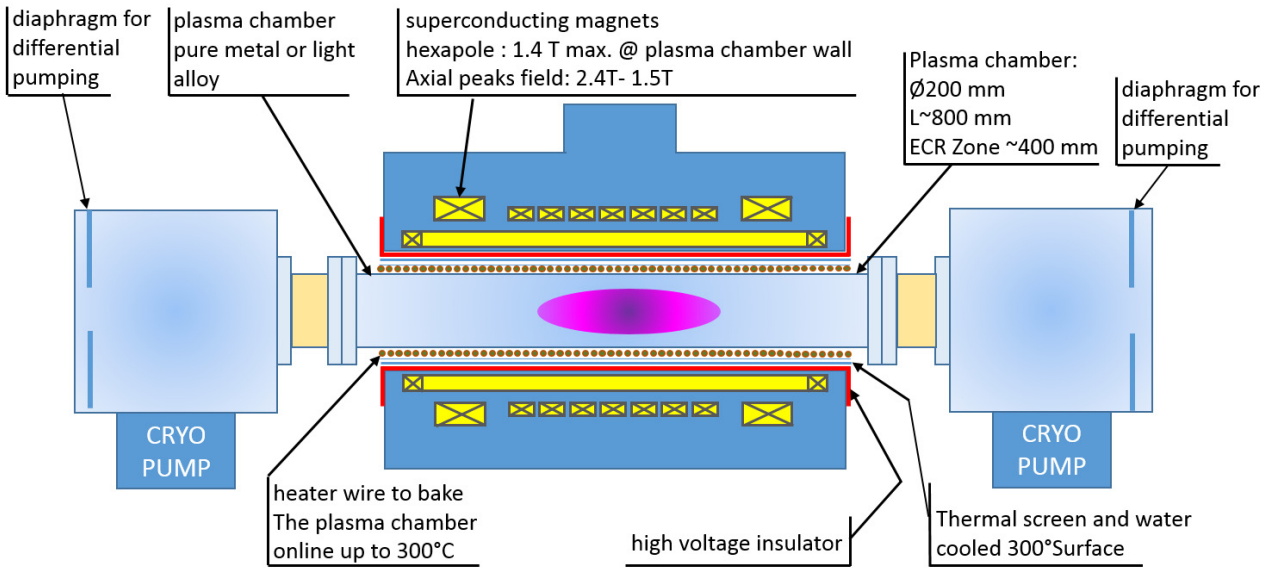

Figure 6: Sketch showing the general features of a new generation ECR CB suitable for EURISOL facility with highly enhanced performances.

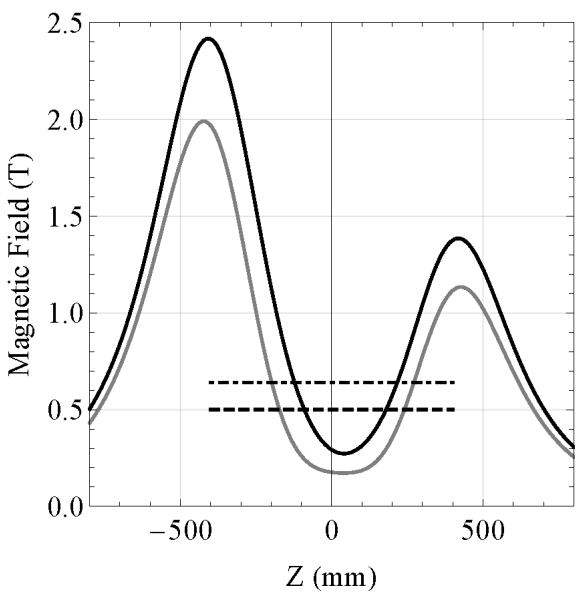

Figure 7: Typical axial magnetic field profile obtainable with the 8 coils proposed for the booster upgrade. Black: 18 GHz profile, Gray: 14 GHz profile. Dashed line: 0.5T (14 GHz resonance). Dotted dashed line: 0.64 T (18 GHz resonance).

The plasma chamber inner bore diameter is 200 mm and its length is 800 mm. The magnet warm bore has a diameter larger than the UHV flanges ones located at each end to ease the assembly/disassembly. The plasma chamber temperature is both controlled by a heating wire and an air cooled tube in order to control the wall temperature from 20°C to 300°C during operation. The heating/cooling plasma chamber system is surrounded by a radiation shield screen and next a water cooled layer fixing the temperature to ambient. The magnet cryostat is set to ground and separated from the high voltage part by a thick plastic insulator in PEEK or high density polyethylene. The UHV is maintained by a set of cryogenic pumps located on both ion source ends. The surrounding vacuum chambers are fully bake able. Diaphragms are placed around the beam axis to limit any contamination coming from downstream of upstream beam line. The whole parts facing the ECR plasma and composing the vacuum chambers in sight of ion injection and extraction system (not represented in Fig. 7) are made with the same material to minimize the chemical species contamination of the plasma due to sputtering. A candidate for the chosen material is pure beryllium (see former section). Insulators can be done with beryllium oxide or alumina.

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