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CONTAMINANTS REDUCTION IN ECR CHARGE BREEDERS BY LNL LPSC GANIL COLLABORATION

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Abstract

Contaminants reduction in Electron Cyclotron Resonance Charge Breeders (ECRCB) is a key point for the future experiments foreseen at LNL and GANIL Isotope Separation On Line (ISOL) facilities. According to the mass separator resolution set downstream the ECRCB, the radioactive ion beam study can be challenged in case of low production rate. An ongoing collaboration between LNL, LPSC and GANIL laboratories aims to improve the beam purity, acting on all the pollutant causes. Comparative experiments will be done at LPSC using different techniques, like covering the plasma chamber wall with liners of different materials. Different configurations of the ECRCB will also be tested, with the enhancement of the efficiency and charge breeding time parameters as additional objectives. A presentation of this program is proposed together with the recent upgrade of the LPSC 1+N+ test bench, with the aim to improve the vacuum quality.

INTRODUCTION

The PHOENIX type charge breeder (CB) has been developed at LPSC since 2000 [1]. It is a minimum-B Electron Cyclotron Resonance (ECR) ion source working at 14.5 GHz which is tested on the 1+N+ test bench. Its latest improvements led to progress in terms of efficiency and charge breeding time [2]. Another important parameter to qualify the ECRCB is the contamination yield. In the present European context, with the SPES and SPIRAL1 upgrade projects respectively under construction and already into operation [3, 4], the contaminants reduction is a key point with regard to the foreseen Radioactive Ion Beam (RIB) production yield and resolving power of downstream separators. These facilities are equipped with PHOENIX Charge Breeders in configurations close to the LPSC one. Thus, LNL, LPSC and GANIL decided to collaborate on the contaminants reduction acting on all the polluting sources, on the basis of a previous agreement signed between LNL and LPSC in 2018. A development plan was defined for the LPSC CB to continue improving its performances and to test the solutions retained by the collaboration. The first step, aiming to improve the 1+N+ test bench vacuum and verify the experimental technique to measure the contaminants level was completed in January 2020. The next two steps will consist in modifying the source magnetic structure and the plasma volume.

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CONTAMINANTS PROBLEM

The ECRCB principle is based on the use of an ECR plasma to multi-ionise an injected 1+ beam. In addition to the injected ion species and the support gas species, contaminants ion beams are extracted from the CB. The origin of these contaminants has already been studied [5–8]. Taking into account the PHOENIX CB configuration and the measurements previously done, the contaminants and their estimated fluxes are indicated below as a function of their origin.

The first cause is the species in the residual vacuum, including the potential leaks with ambient atmosphere, wall outgasing, o-rings permeation and vacuum parts cleaning. Analysing A/q spectrum from the CB running in the 1+N+ configuration, these fluxes are estimated between 10^{12} and 10^{13} pps.

The second one comes from the impurities and unwanted isotopes present in the support gas. 99.999% purity gas are typically used in the CB, and impurities like H_2O, O_2, N_2, CO or hydrocarbons are present with proportions of 20 ppm or less for the gas species usually used (H_2, He, O_2). Taking into account the support gas fluxes deduced from the measured spectrum, the contaminants flux originating from the support gas is estimated at 10^9 pps.

Finally, the plasma confinement being imperfect, the plasma ions intercept the chamber wall. Depending on their charge state and the plasma potential, their energy can reach several hundreds of eV, leading to sputtering of the wall material. Thus, the plasma parameters influence the contamination. It was also demonstrated that an unstable plasma regime could lead to a higher production of contaminants [9]. From this last data, the contaminants fluxes caused by sputtering can be estimated at 10^{12} to 10^{13} pps.

On the other hand, RIB fluxes in the 10^2 to 10^{10} pps range are expected to be injected into the SPES and SPIRAL1 upgrade charge breeders [10]. Taking into account the CB efficiency and the resolving power of the downstream separators, these contaminant yields must be minimised not to compromise physics experiments [8, 11].

SOLUTIONS TO CONTAMINATION PROBLEM

To reduce efficiently the contamination yield, all the sources must be reduced [8].

First, particular attention must be paid to the vacuum chambers and vacuum parts cleaning. Several techniques

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have shown their efficiency. The vacuum level must be as low as possible using Ultra High Vacuum (UHV) standards, suppressing o-rings and baking-out sections and parts [12]. The use of the same material is mandatory for the parts surrounding the plasma and for the electrodes. The material has to be as pure as possible, being preferably mono-isotopic. A possible choice could be the deposition of a specific material, the disadvantage being that depending on the thickness and the CB operation conditions, the layer can have a short lifetime. Concerning the support gas, in the case of H_2 or He, one solution proposed by ANL [13], consists in adding a cryogenic system on the gas circuit in order to condensate the contaminants. A baking system could also be added to outgas the circuit before operation.

PRESENT CONFIGURATION OF THE LPSC 1+N+ TEST BENCH AND CHARGE BREEDER

1+N+ Test Bench

The 1+N+ test bench was assembled in 2002 to test the charge breeding method with a PHOENIX type ion source [14]. The "1+" beam line is used to generate the 1+ beam and inject it into the CB. It is composed of the 1+ source, a 90° dipole magnet, two emittance scanners, one Faraday cup (FC) and the injection optics. The analysis of the beams extracted from the CB is done in the "N+" beam line. It consists of the CB extraction and optics, a 120° dipole magnet, two emittance scanners and one FC.

Along the years, the 1+N+ test bench was gradually modified for example to increase the high voltage insulation and adapt new diagnostics. Most of the sealing was done using o-rings. The vacuum system was composed of 16 turbo pumps with pumping speed between 240 and 360 $l \cdot s^{-1}$. Oil sealed rotary primary pumps were used in the past and after years of operation, dust accumulated on some surfaces, notably because of pumping oil vapors backstreaming. The vacuum level in the beam line was between 2×10^{-7} mbar and 5×10^{-7} mbar, the typical vacuum level at the CB injection during operation being 7×10^{-7} mbar.

Charge Breeder

Like the other PHOENIX type ion sources, the LPSC charge breeder structure is modular, see Fig. 1. The external part aims to generate the axial magnetic field. It is composed of three pairs of coils (orange) stack assembled with soft iron rings (blue). Inside, the central core is made up of the stainless steel plasma chamber (black) surrounded by the hexapole (green). The plasma chamber has an internal diameter of 72 mm and the hexapole generates a 0.8 T radial magnetic field strength in front of the poles, at the plasma chamber wall surface. The injection plug, extraction plug, surrounding hexapole rings and additional injection plug (blue) set under vacuum into the plasma chamber, parts of the central core, complete the axial magnetic field system.

Two wave guides are machined directly into the additional plug for the microwave coupling; in addition a piece of wave guide made of brass is fixed at the plug extremity. In this configuration, the plasma chamber wall is cylindrical without port. A 40 µm Nickel plating was done on the extraction plug and on the additional injection one to reduce the outgassing under vacuum. A 5 µm Silver plating was added on the additional injection plug to increase the electrical conductivity. A vented plasma electrode with a 8 mm hole, made of 2017A aluminum alloy, closes the plasma chamber at extraction. In this configuration, a great number of material is present in front of the plasma.

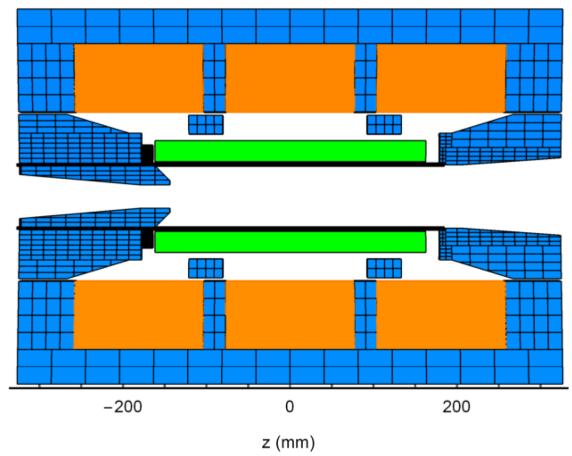

Figure 1: Cut view of the CB configuration.

In order to improve the CB performances, LPSC defined a 3 steps development plan, in collaboration with LNL and GANIL to address contaminants reduction. The first step, completed in January 2020, aimed to improve the vacuum and devices alignment of the 1+N+ beam line. The next step goal will be to modify the axial magnetic system to optimize the field profile while reducing the cross talk between the coils. In this configuration, contaminants reduction experiments will be tested. Comparative measurements will be done to check the efficiency of the different solutions adopted, measuring A/q spectra. A resolving power as high as possible will be necessary to separate the peaks. The measurement method will be verified and the limits evaluated. Finally, the last step will consist in increasing the plasma volume to increase the production of higher charge states [15] and pursuing studies on the contaminants reduction.

CONTAMINANTS MEASUREMENT METHOD

Considering that the contaminant ions originate from the CB plasma, the experiments will be carried out with the CB in "source mode" that is without 1+ beam injection. First, spectra will be acquired with the N+ FC to obtain the absolute value of the more intense species. Then emittance measurements will be done in the horizontal N+ emittance scanner FC. In this case, the 0.2 mm slits will produce a higher resolution, at the expense of cutting a large fraction part of the beam. In order to measure the spectrum, the potential applied to the deviating plate of the emittance scanner

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will have first to be optimised on a peak. The comparison of the spectra measured in the FC and in the emittance scanner will allow defining a rough correction factor that will be used to obtain an estimate of the absolute value of the contaminant peaks.

CB DEVELOPMENT PLAN

1+N+ Beam Line Upgrade

The 1+N+ beam line upgrade was realized between September 2018 and January 2020. To minimize the duration of the shutdown, all beam line sections were disassembled at the same time and many modifications were done simultaneously.

Modifications Different solutions were used to upgrade the seven vacuum chambers to UHV standards. The conflat (CF) standard was chosen for all flanges. Three vacuum chambers were replaced by new ones whereas the others were modified. The vacuum valves mounted on the chambers were either cleaned or replaced by new ones.

For alignment, an optical level was set on the beam axis and beam line elements, equipped with removable centered targets, were positioned. This method requires to place targets on the room walls and to have a clear view through the beam line. For this last reason, two view ports were added on the 1+ and N+ dipole magnet chambers and corresponding grooves were machined on their yoke.

All the beam optics elements under vacuum were replaced to be UHV compatible, using alumina as insulating material and 304L stainless steel for metallic parts. The electrical feedthroughs were also replaced, using only brazed alumina sealing. A new 1+ beam electrostatic deviating system was manufactured. To reduce aberrations, the injection double lens assembly was redesigned: the new electrodes have an internal diameter of 80 mm (previously 60 mm).

At extraction, a new assembly composed of the puller and the Einzel lens was designed and manufactured. The new puller has a conical shape to improve the beam extraction and 32 holes were machined to enhance the vacuum pumping. The extraction lens, earlier realized by a simple cylinder set into the extraction chamber [16], was replaced by a three cylindrical electrodes Einzel lens, having a 80 mm inner diameter.

Concerning the diagnostics, the three FC were replaced by new electrostatic ones, based on the same design and with a fully shielded cup. Two new emittance scanners will be adapted and installed on the 1+ section. The N+ emittance scanners were modified to allow pumping, replace the insulation parts by alumina ones and replace the cables under vacuum by UHV models. Their support flange was also upgraded to CF standard.

The vacuum system was completely revised. For the UHV pumping, a new Agilent Twistor 304 FS ($250 \mathrm{l} \cdot \mathrm{s}^{-1}$ pumping speed) was installed on the 1+ source section. Six Oerlikon turbovac 361 pumps were modified to CF160 flange standard and cleaned by the manufacturer. In this configuration, their pumping speed is $400 \mathrm{l} \cdot \mathrm{s}^{-1}$. One was installed on the 1+ diagnostic section, two on the injection section, two on the extraction section and one on the N+ diagnostics section. All UHV gauges were replaced by Pfeiffer IKR 251 model on CF flanges. The whole vacuum circuit was disassembled and cleaned. A maintenance and a cleaning of the primary dry pump, model Agilent triscroll 300, was also realized.

The largest parts, including the vacuum chambers and most of the flanges, were degreased, etched, rinsed with high pressure water, rinsed with demineralized water and dried. The other parts were degreased, ultrasonic cleaned and dried. All the parts were re-assembled, aligned and set under vacuum. In this configuration, twelve sealings with o-rings remain on the beam line, notably two for the 1+ source, six at the CB injection and three at the CB extraction. In the next CB configuration, the number of o-rings will be reduced, using new alumina CB insulators with brazed metallic flanges. Section by section, a methodical vacuum leak detection was applied to all the welds and connections. In this configuration, without baking the chambers, the pressure in the beam line sections is in the range 3×10^{-8} mbar to 6×10^{-8} mbar, the pressure at the CB injection being 4×10^{-8} mbar. Therefore the residual pressure was reduced by an order of magnitude thanks to the performed modifications while reducing the number of pumps.

Qualification experiments To qualify the test bench, it was decided to compare the charge breeding spectra of K with respect to the one obtained before the upgrade, the tuning being optimised for the K^{10+} charge breeding with He as support gas, see Fig. 2. The new performances being in good agreement with the previous ones, the 1+N+ test bench operation was validated.

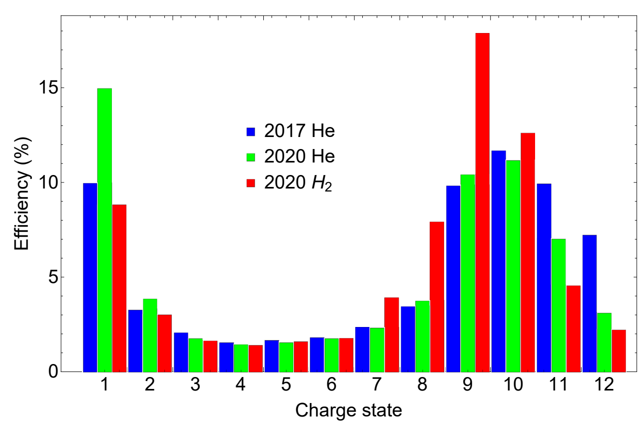

Figure 2: Measured K charge breeding spectra blue) in the previous configuration with He as support gas, green) after the 1+N+ test bench upgrade with He as support gas and red) after the 1+N+ test bench upgrade with H_2 as support gas.

The K^{10+} efficiency is measured at 11.2% and found slightly lower than the previous best measured efficiency at 11.7% [2]. A slight shift toward lower charge states is also noticed together with a lower 1+ beam capture. The

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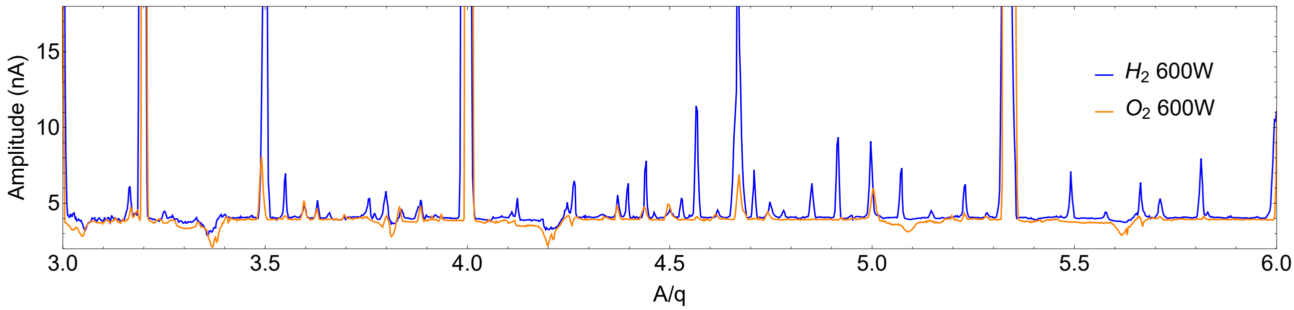

Figure 3: High resolution spectra with H_2 and O_2 as support gas and 600 W of microwave power.

difference is attributed to an incomplete conditioning of the CB before the experiments. Using H_2 as support gas, the best efficiency was found at 17.9% for K^{9+}.

Contaminants Reduction Preliminary Experiments To estimate the resolving power of the contaminants measurement method, the CB was operated with natural Xenon as support gas and a spectrum was measured with the horizontal emittance scanner. By analysing the separation of the $^{131}Xe^{19+}$ and $^{132}Xe^{19+}$ peaks, which have a A/q ratio near 7 and similar peak amplitudes, the resolving power was estimated at 1:150.

After this experiment, the contaminants measurement method was tested by studying the influence of the support gas species and of the microwave power on the contaminant beams. As a similar operating regime cannot be reached for different support gas, we decided for each support gas species, to tune the CB (support gas dosing, coils...) optimizing the K^{10+} charge breeding efficiency with the same microwave power 600 W. Contaminant spectra were recorded in this configuration, without 1+ beam injection, together with 100, 300 and 450 W microwave power values, as illustrated in Fig. 3.

The measurements analysis shows several limitations. First, the signal over noise ratio is low, the minimum measurable peak amplitude being on the order of 100 epA. This level corresponds roughly to an absolute level of contaminants of 10^{10} pps in the FC. As a comparison, a 10^8 pps flux at the CB entrance would give a 10^7 pps flux in the N+ FC, considering a 10% efficiency. Moreover the minimum step in A/q is too large which leads to imprecise peak value measurement. This limitation comes from the poor resolution of the data acquisition system which generates the analog signal driving the dipole power supply. Finally, dips with negative intensity values are also visible in the spectra, probably due to secondary emission electrons, induced by a neighbour intense beam touching the wall, coupling to the emittance scanner FC through the device pumping holes.

The measurement method will be implemented to solve these problems. The resolution of the data acquisition system will be improved to allow smaller steps in A/q. Instead using the emittance scanner, a slit will be set in the N+ diagnostics section and the measurements will be done in the N+ FC. In this way, at ANL, 1 epA contaminants peaks was measured [8]. Other type of detectors could also be tested with a principle based on the use of a channeltron or a plastic scintillator coupled with a photodiode, the goal being to increase the sensitivity.

For each high resolution spectra, the A/q value of all the peaks was listed. After analysis, the most probable species found for these distributions is in good agreement with the elements cited in the "Charge Breeder" section as possible contaminants with notably Fe, Ni, Mo, Sn, Zn, Cu coming from the wall sputtering and gaseous elements like H, N, O, Xe, Kr or Ar originating from the residual vacuum.

The resolving power is insufficient to separate all the species, most of the peaks being due to the superposition of several possible species. Some peaks are also found to correspond to a single species. For some isotopes, the evolution of the peak amplitude is represented as a function of the microwave power and support gas species, see Fig. 4.

The contaminants production is favoured when using H_2 as support gas, this is also true for most of other peaks, see Fig. 4. $^{96}Mo^{15+}$ and $^{12}C^{5+}$ clearly increase with microwave power whatever the support gas which shows a dependency to the microwave power and so to the plasma density. For $^{40}Ar^{7+}$ the yield is almost constant when increasing the microwave power.

Five Coil CB Configuration

The next step of the development plan consists in optimizing the CB magnetic configuration. The new design was simulated to enhance the magnetic field profile by rearranging the yoke and coils structure and changing the shape of the soft iron plugs (see Fig. 5). One coil of the central pair will be removed and the distance between the coils will be increased to reduce the cross talk. The length of the CB will decrease from 640 mm to 560 mm. The injection and extraction plugs will be shortened, improving the beam injection and extraction. This new configuration is called "Five coil configuration".

The modification of the LPSC CB assembly is planned before the end of 2020, the last parts are being manufactured. Contaminants reduction experiments will be done by introducing liners to cover the plasma chamber wall, the injection plug and the plasma electrode. These measurements will be compared to results previously obtained without liners. Three different liner materials will be tested: Nb, Ta and alu-

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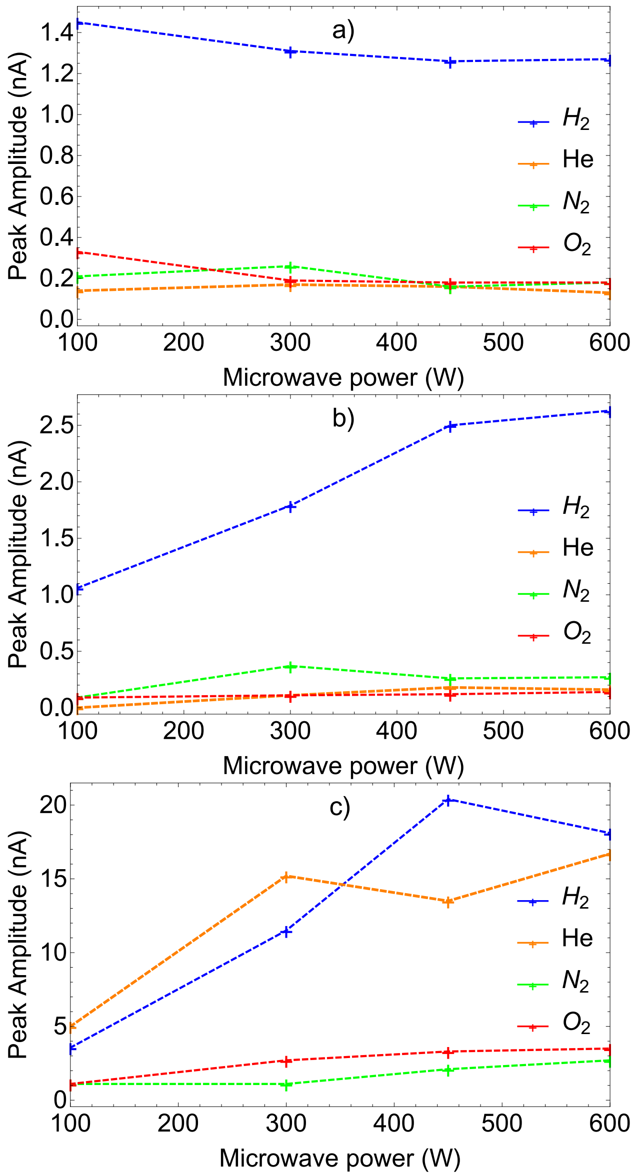

Figure 4: Evolution of a) $^{40}Ar^{7+}$, b) $^{96}Mo^{15+}$ and c) $^{12}C^{5+}$ peak amplitude as a function of microwave power and CB support gas plasma species.

mina. For this last case, the Metal Dielectric liner technique developed at NIPNE [17] is foreseen. A few micron alumina layer is created by special electrochemical deposition on a 99.999% purity aluminum foil. In this five coil configuration, liner parts will be installed through the CB injection port only, without dismounting the extraction. A gas circuit, still to be designed, will also be implemented for the support gas contaminants reduction.

Large Diameter Configuration

The last step of the development plan is called "Large diameter CB configuration". The goal in this case will be to favour the production of highly charged ions by increasing the plasma volume and consequently the ions lifetime within the plasma. This solution, successfully tested on the

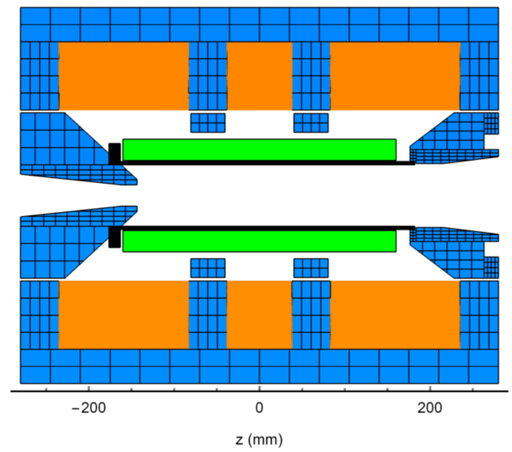

Figure 5: Cut view of the CB five coils configuration.

PHOENIX V3 ion source [15], will be applied to the CB: the plasma chamber diameter will be increased to 100 mm. This configuration should also reduce contamination thanks to a more favorable volume over surface ratio for the plasma cavity [11]. The hexapole was designed to obtain a 1.0 T radial magnetic field at the new plasma chamber wall, in front of the pole. Preliminary magnetic simulations were performed to conceive the axial field system, but the definitive design remains to be done. The material tested for the liners experiments in the five coil CB configuration could be used to manufacture some central core parts of the large diameter CB.

CONCLUSION

A collaboration between LNL, LPSC and GANIL, was inititated on the contaminants reduction and a R&D program was defined and integrated into the LPSC CB development plan. The 1+N+ test bench upgrade reduced the residual pressure throughout the beam line by a decade. Preliminary experiments have shown a high level of contaminants, notably originating from sputtering of the walls surrounding the plasma. The pollutant level was found to be higher with H_2 as support gas and some species tend to increase with the plasma density. Limitations in the detection method were observed and solutions were identified to enhance the sensitivity and precision of the measurements. The LPSC CB will be assembled in the new five coil configuration before the end of 2020 and the solutions defined to reduce the contaminants, like the use of liners, will be tested.

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