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# PIPERADE: A double Penning trap for mass separation and mass spectrometry at DESIR/SPIRAL2

- <sup>3</sup> P. Ascher<sup>*a*,\*</sup>, L. Daudin<sup>*a*</sup>, M. Flayol<sup>*a*</sup>, M. Gerbaux<sup>*a*</sup>, S. Grévy<sup>*a*</sup>, M. Hukkanen<sup>*a*,*b*</sup>, A. Husson<sup>*a*</sup>,
- A. de Roubin<sup>a</sup>, P. Alfaurt<sup>a</sup>, B. Blank<sup>a</sup>, K. Blaum<sup>c</sup>, B. Lachacinski<sup>a</sup>, D. Lunney<sup>d</sup>,
- <sup>5</sup> E. Minaya Ramirez<sup>d</sup>, S. Naimi<sup>e</sup>, S. Perard<sup>a</sup> and B. Thomas<sup>a</sup>

6 <sup>a</sup>Université de Bordeaux, CNRS/IN2P3, CENBG, UMR5797, 33175 Gradignan, France

7 <sup>b</sup>University of Jyväskylä, P.O. Box 35, FI-40014 Jyväskylä, Finland

8 <sup>c</sup>Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

<sup>9</sup> <sup>d</sup>Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France

10 <sup>e</sup>RIKEN Nishina Center, Wako, Saitama 351-0198, Japan

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# ABSTRACT

A double Penning trap is being commissioned at CENBG Bordeaux for the future DE-SIR/SPIRAL2 facility of GANIL. The setup is designed to perform both high-resolution mass separation of the ion beam for trap-assisted spectroscopy, and high-accuracy mass spectrometry of short-lived nuclides. In this paper, the technical details of the new device are described. First offline tests with the purification trap are also presented, showing a mass resolving power of about 10<sup>5</sup>.

# <sup>22</sup> 1. Introduction

The use of ion traps in radioactive ion beam (RIB) facilities has become essential these last decades [1, 2], both for 23 beam quality/purity improvement and for high-accuracy mass spectrometry. After the pioneering ISOLTRAP experi-24 ment at ISOLDE/CERN [3], Penning traps have been implemented in various facilities, such as JYFLTRAP/IGISOL 25 [4], LEBIT/MSU [5], TITAN/TRIUMF [6], SHIPTRAP/GSI [7], CPT/CARIBU [8] and TRIGA-TRAP/TRIGA [9], 26 all of them showing that this technique, widely used in other fields (atomic physics, quantum computing, ...), is also 27 extremely powerful in terms of nuclear mass precision, accuracy, sensitivity, efficiency as well as ion manipulation for 28 high-resolution beam purification. 29 In this context, a double Penning trap named PIPERADE (PIèges de PEnning pour les RAdionucléides à DEsir, 30 i.e. Penning traps for radionuclides at DESIR) [10, 11] is being developed at Centre d'Etudes Nucléaires de Bordeaux-31

 Gradignan (CENBG) for the future DESIR/SPIRAL2 facility [12, 13] of GANIL. DESIR will be dedicated to lowenergy studies through precision measurements of nuclear ground and excited state properties. Decay spectroscopy, laser spectroscopy and trap-based devices will benefit from new 10-60 keV exotic ion beams from: (i) the upgraded
 SPIRAL1 facility [14], producing light nuclei by ISOL-fragmentation and (ii) the super separator spectrometer S3
 [15] under commissioning, producing a wide range of neutron-deficient nuclei (including the refractory elements) by

<sup>37</sup> in-flight fusion-evaporation with unprecedented intensities. A second phase may well emerge in the SPIRAL2 project,

<sup>38</sup> providing the accessibility to very neutron-rich nuclei by fission reactions.

<sup>39</sup> DESIR will thus be unique in terms of beam intensities. While the production rate is crucial to study exotic nuclei, <sup>40</sup> beam purity is also critically important. Isobaric contamination from non-selective ion production and/or ionization,

as well as chemical reactions producing molecular contaminants, are often present with much higher intensities than

the ions of interest, preventing certain types of measurements.

Beam purification can be performed using a magnetic dipole separator, such as the DESIR-HRS [16] developed at CENBG for DESIR. It has the advantage to be extremely fast (in-flight separation, i.e. a few tens of  $\mu$ s), to be able to handle high-intensity beams and it aims to push the current mass resolution limits of such a system, up to 2 × 10<sup>4</sup>.

\*Corresponding author ascher@cenbg.in2p3.fr (P. Ascher) ORCID(s): 0000-0002-1990-0848 (P. Ascher)

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Nevertheless, even a higher resolution is required to separate a few ions of interest from a large number of con-46 taminants, and more generally to separate very close isobars or even long-lived isomers. Indeed, high-precision mea-47 surements can be achieved only if the beam is isobarically-pure but also isomerically-pure. Penning traps are known 48 to reach the highest resolving power, from  $10^5$  to  $10^7$  depending on the separation techniques, such as the standard 49 sideband buffer gas cooling [17], Ramsey cleaning [18, 19] or phase splitting [20, 21, 22]. All these techniques will be 50 presented in this paper. However, the high-resolution performances of the Penning trap technique come at the price of 51 long separation times (> 100 ms) and limited numbers of ions, up to  $10^2$ - $10^3$  ions per bunch for the buffer gas cooling 52 technique and only a few ions per bunch for the other methods. This is a consequence of space-charge effects which 53 decrease the resolution and the efficiency for larger number of ions [23]. In order to push the limitations of existing 54 devices further, the first trap of the double Penning trap PIPERADE will be a new type of high-capacity large trap 55 that aims to separate up to  $10^4$ - $10^5$  ions per bunch using the buffer gas cooling technique. In addition, other cleaning 56 techniques allowing to reach the highest resolution, and requiring a gas-free trap, will be implemented in the second 57 trap. 58

The pure beams extracted from the device will be re-injected in the main DESIR beam line, so that various experimental setups, such as total absorption spectrometry, collinear laser spectroscopy and decay measurements, will benefit from the trap performances.

Besides purification purposes, PIPERADE will be used as a mass-measurement setup on its own. The mass of 62 an atomic nucleus is one of its most fundamental properties and is therefore a key observable to guide and constrain 63 the current theoretical descriptions of the nucleus and the nucleon-nucleon interaction. Binding energy measurements 64 along isotopic chains reveal structure effects [24], such as shell closures [25, 26] or onsets of deformation [27]. In 65 addition to fundamental nuclear physics questions, experimental masses are crucial to constrain nucleosynthesis mod-66 els [28, 29] (rp-process and r-process) and precise Q-value measurements of specific beta transitions have different 67 applications, as tests of the weak interaction in the Standard Model [30] or the search of candidates for the neutrino 68 mass measurement [31]. 69

In this paper, details on the Penning trap technique will be given, followed by a full technical description of the
 PIPERADE system. The setup being now fully in operation, the tests with offline beam are ongoing ; first results using
 the first trap will briefly be presented whereas a detailed description of the offline studies will be given in another
 publication, in preparation.

# **2.** Basics of Penning traps and operational modes of PIPERADE

# 75 2.1. Principle of a Penning trap and excitation techniques

A Penning trap allows the storage of charged particles thanks to the combination of a strong homogeneous magnetic field for the radial confinement and a static quadrupole electric field for the axial confinement. The electric potential is obtained by applying a voltage difference  $U_0$  between a central ring electrode and two so-called endcap electrodes and can be expressed as

$$V(z,\rho) = \frac{U_0}{d^2} (2z^2 - \rho^2)$$
(1)

where z is the distance along the trap axis from the trap center,  $\rho$  the radial coordinate, and  $d = \sqrt{z_0^2 + r_0^2/2}$  the characteristic trap geometry parameter, with  $z_0$  the distance between the ring center and the endcaps, and  $r_0$  the inner trap radius. The repulsive character of this electric field in the radial direction is compensated by the strong magnetic field obtained by installing the Penning trap in a superconducting magnet. For creating this quadrupole electric field, electrodes can be shaped as hyperboloids of revolution. An alternate way is to use a cylindrical trap and by choosing the potentials and lengths of the electrodes appropriately [32], the electric field can be made very close to a pure quadrupolar one near the trap center. It is the case of the PIPERADE traps, which are shown in Figure 1.a).

The resulting ion motion in a Penning trap is a superposition of three eigenmotions: (i) an harmonic axial motion along the trap axis at the frequency  $v_z$ , (ii) a modified cyclotron motion at the frequency  $v_+$ , and (iii) a magnetron motion at the frequency  $v_-$ . The two latter motions are in the radial plane, the slow magnetron motion is centered at the trap axis and its orbit defines the center of the modified cyclotron motion. The true cyclotron frequency  $v_c = qB/2\pi m$ , with q the ion charge, m the ion mass and B the strength of the magnetic field, corresponds, for an ideal trap, to the

<sup>92</sup> sum of the two radial frequencies.



**Figure 1:** a) The two Penning traps of PIPERADE separated by a diaphragm. The purification trap (PT) consists of eleven electrodes, i.e. two endcap electrodes, which are four-fold axially-segmented (PE1-PE4, PE5-PE8), two correction electrodes (PC1, PC2) and one central ring electrode (PR). The measurement trap (MT) consists of five electrodes, i.e. two endcap electrodes (ME1, ME2), two correction electrodes (MC1, MC2) and one central ring electrode (MR). The electronics for broad-band FT-ICR detection can be seen on top of the purification trap. Gas inlets for helium feedings are fixed on the adaptation electrodes on the far sides of the purification and measurement traps. b) Schematic view of the central ring electrodes of PT and MT. Dipolar excitation at  $v_{-}$  is shown in red, dipolar excitation at  $v_{+}$  is shown in blue, whereas quadrupolar excitation at  $v_{c}$  is shown in green.

The main interest of a Penning trap lies in the manipulation of these ion motions. Each motion has its own fixed frequency, defined by the electric and magnetic fields and the charge-to-mass ratio q/m of the trapped ions. However, the amplitude of these motions can be modified by bringing/removing energy to/from the motions. There are different ways of doing so, one being to fill the trap with a buffer gas. The ion collisions with the gas atoms will lead to a fast decrease of the amplitude of both the axial and the modified cyclotron motions, whereas the magnetron motion radius will slowly increase.

The second powerful way to manipulate the ions is to apply radio-frequency (RF) fields on the trap electrodes. Excitations of the axial motion can be performed by applying RF fields on the endcaps, but in the following only radial motion excitations will be described. For this, the central ring electrode is used and has to be segmented. In the case of PIPERADE, as can be seen in Figure 1.b), the ring electrode of the first trap, called the purification trap (PT), is 8fold segmented whereas the ring electrode of the second trap, called the measurement trap (MT), is 4-fold segmented. There are two main modes for performing excitations: the dipolar and the quadrupolar modes.

The dipolar mode consists of applying an RF field in one radial direction. If the RF signal is applied at one of 105 the eigenfrequencies, the radius of the corresponding motion will be modified without changing the others. When the 106 excitation and the ion motion are in phase, the ions will be pushed from the electrode where the RF signal is applied 107 every time it passes in front of it, and therefore the radius will increase. Figure 1.b) shows how the two different dipolar 108 excitations at  $v_{-}$  or  $v_{+}$  are applied on the ring segments. One should note that each trap segment is connected to a 109 given function generator providing a specific frequency and phase. For the purification trap, opposite phases 0 and  $\pi$ 110 are applied on opposite segments whereas for the measurement trap, only one phase is applied on a single segment, 111 also creating a dipolar field component but with lower amplitude. 112

The quadrupolar mode consists of applying an RF signal with the same phase on two opposite segments (see  $v_c$ 113 excitation in Figure 1.b). For the purification trap, the same RF signal with the opposite phase is additionally applied 114 to the two other orthogonal segments for a higher quadrupolar field component. This type of field is applied only on 115 sums of eigenfrequencies and allows to couple motions. A quadrupolar RF excitation at  $v_c = v_+ + v_-$  will couple the 116 modified cyclotron motion to the magnetron motion, i.e. as long as the excitation is applied there will be a periodic 117 conversion between the amplitudes of both motions. Therefore, what is called a  $\pi$ -pulse excitation corresponds to a 118 single conversion from a pure motion to another pure one. The period of the interconversion process depends on the 119 amplitude of the excitation field. An alternate way to couple the radial motions is to use an octupolar mode, which 120 increases the resolving power [33]. This is technically achieved by using an 8-segmented ring like the purification trap 121 and by applying the same phase on the four opposite segments at the frequency  $2v_c$ . 122

These dipolar and quadrupolar fields are usually applied by one RF pulse at a given amplitude and for a given duration, which will be inversely proportional to the frequency width of the excitation. Therefore the longer the excitation, the higher the resolution. An alternate way is to use time-separated oscillatory fields, called Ramsey fields [18, 34], by applying two identical pulses separated by a certain time duration, which increases the resolution and the precision of the technique, as it will be explained in the next Section.

#### 128 2.2. Mass separation and mass spectrometry techniques

All the various mass separation and mass measurement techniques that will be used at PIPERADE will be based on the above-described manipulation methods. The double-Penning trap PIPERADE device consists of two cylindrical traps, separated by a diaphragm for selection purposes but also to act as a pumping barrier. Indeed, depending on the operational mode the pressure in both traps will have to be different. These different techniques and the main operational modes of PIPERADE are described in the following.

#### 134 2.2.1. PIPERADE as a mass separator

PIPERADE will be used for mass separation and will deliver pure beams to the DESIR users for post-trap spec-135 troscopy. The standard separation technique, which will be used in the purification trap of PIPERADE is the so-called 136 sideband buffer gas cooling technique [17]. It consists of two main steps: first a dipolar excitation is applied at the 137 magnetron frequency  $v_{-}$ . This frequency being in first-order mass-independent, it results in an increased magnetron 138 radius for all ion species in the trap. The second step uses the combination of a quadrupolar field at  $v_c$ , which converts 130 the magnetron motion into a modified cyclotron motion, and the effect of the buffer gas, which cools the modified 140 cyclotron motion. As the quadrupolar excitation is highly selective, only the ions of interest are re-centered in the trap. 141 By ejecting the ions through the diaphragm, only the re-centered ones are transferred to the measurement trap. This 142 powerful technique has the advantage of removing multiple contaminants, even unidentified ones, to handle large ion 143 bunches (up to  $10^2$ - $10^3$  ions) and to reach resolutions up to  $10^5$ . The limitation in terms of number of ions is due to 144 space-charge effects, leading to frequency shifts, peak broadening and screening effects, which makes the re-centering 145 inefficient [23, 35]. As it is shown for example from simulations in [10], reducing the cloud density, i.e. expanding 146 the cloud for a given number of ions, is a way to limit these space-charge effects. By increasing the trap size, the field 147 anharmonicities are further from the center thus the cloud size can be larger. This is why the purification trap of PIPER-148 ADE has a large diameter (64 mm) and aims at separating larger ion bunches (more than  $10^4$  ions). More recently, 149 promising variants of this sideband buffer gas cooling technique have emerged, such as the octupolar excitation for the 150 re-centering [36] or the so-called buffer-gas-free SIMCO excitation [37]. They will be studied using PIPERADE. 151

The purification trap will mostly be used for sideband buffer gas cooling, whereas the measurement trap could be used for accumulation purposes. One can repeat the purification cycle by sending each time a newly cleaned sample to the measurement trap, where He gas is injected for an efficient trapping. Once the accumulated sample is large enough for a measurement, a final cleaning is needed to get rid of the daughter nuclei produced during the accumulation time and the highly-purified sample of ions of interest can be sent to the downstream experiments.

The measurement trap could also be used for further high-resolution mass separation. With very few ions and in a gas-free trap, other techniques can be used to reach a very high resolving power and separate close isobars or isomers. The so-called dipole cleaning can be used by applying a dipolar field at the modified cyclotron frequency  $v_+$  of a wellknown contaminant, whose radius is increased enough to not be extracted from the trap. By applying time-separated pulses, as described in the previous section, the so-called Ramsey cleaning is very powerful for a highly-selective cleaning of a given contaminant. More details can be found in [19]. Such cleaning methods can reach resolutions up to about  $10^6$ , which makes this technique also suitable for isomeric cleaning.

Finally, a very recent method, which has been implemented at JYFLTRAP for post-trap spectroscopy, is the phase-164 splitting method, inspired by the Phase-Imaging Ion-Cyclotron-Resonance (PI-ICR) measurement technique [20]. De-165 tails can be found in [21, 22]. The first step of this method is to excite the modified cyclotron motion of the trapped 166 ions by applying a short broad-band dipolar excitation. The excitation being short, it is not highly selective and the 167 radial amplitudes of all the isobars and any isomers are thus increased. Then the basic principle of this separation is 168 to let the ions oscillate at the fast modified cyclotron frequency  $v_{\pm}$  for a given time, so that the species are separated in 169 phase. This technique requires the use of a position-sensitive micro-channel plate (MCP) detector, in order to project 170 the radial position of the ion cloud on the detector. One should note here that extracting the ions moving at the higher 171  $v_{\perp}$  frequency will lead to a smearing of the ion spot on the MCP. Therefore, before the ion extraction, a  $\pi$ -pulse excita-172 tion has to be applied to convert the pure modified cyclotron motion into a pure magnetron motion, which then is slow 173



**Figure 2:** Experimental setup at CENBG, consisting of 1) a stable ion source floated at 30 kV, 2) a DESIR - quadrupole triplet, 3) the GPIB (General Purpose Ion Buncher) floated at about 29.9 kV, 4) an electrostatic deflector floated at 27 kV and 5) the 7-Tesla Penning-trap system floated at about 29.95 kV. Faraday cups (FC), beam profile monitors (BPM) and micro-channel plates (MCP) detectors are installed in the beam line for ion beam diagnostics.

enough to observe a well-defined spot on the detector. After the separation, the isobar or the state of interest can be 174 transported to the post-trap spectroscopy device through a diaphragm with a hole at the appropriate angle and radius 175 from the center. The selection method used at JYFLTRAP is to adapt the accumulation time so that the two species 176 are separated by 180 degrees. A magnetron excitation in opposite phase with the motion of the ions of interest will 177 center them in the trap while moving contaminants off-axis [22]. The selection method proposed in [21] is to apply a 178 static excitation, to shift the center of the trap and then re-center the ions of interest. This has never been tested. The 179 phase splitting method is very powerful in terms of resolution, which can even reach  $10^7$  for long accumulation times. 180 In the case of isomeric cleaning, before sending the isomeric beam to post-trap spectroscopy, the excitation energy 181

of the isomeric state could also be measured with the techniques presented in the next section.

# 183 2.2.2. PIPERADE as a mass spectrometer

<sup>184</sup> When using PIPERADE as a mass spectrometer, a highly-purified sample is required. Therefore both traps will still <sup>185</sup> be used for various mass separations explained in the previous section before the precision mass measurement in the <sup>186</sup> second trap is realized. The mass measurement of an ion is performed through the determination of its true cyclotron <sup>187</sup> frequency  $v_c = qB/2\pi m$ . Once the cyclotron frequency is measured, only the magnetic field has to be measured to <sup>188</sup> extract the mass of the ion. This is performed by alternatively measuring the cyclotron frequency of the ion of interest <sup>189</sup> and that of a very well-known reference isotope. Even if the magnetic field is not monitored during the measurement <sup>190</sup> of the ion of interest, if the field drift and fluctuations are small enough, a linear interpolation is sufficient, not to add <sup>191</sup> systematic uncertainties to the measured mass.

The standard technique for cyclotron frequency determination used since decades is the ToF-ICR technique and is described in detail in [38]. The precision achieved with this method is of the order of  $10^{-8}$  for short-lived nuclides. As for the dipole cleaning method, the Ramsey method has boosted this technique, with an increase of a factor of 3 in the precision on the mass determination [18].

A few years ago, the PI-ICR method has been introduced in the field and implemented in many Penning-trap mass spectrometers, such as SHIPTRAP [39] where it was first developed, CPT [40], ISOLTRAP [41] and JYFLTRAP [22]. It has been shown to reach a fivefold gain for the precision on the cyclotron frequency determination compared to the Ramsey ToF-ICR technique. This non-scanning method opens the way to mass measurements of very exotic nuclei but also long-lived isomers, due to the excellent resolution it can reach (see the previous subsection).

# **3.** Overview of the experimental setup at CENBG

The PIPERADE setup is currently being developed and commissioned at CENBG before its currently scheduled installation at DESIR/GANIL in 2024. A FEBIAD ion source is used to produce stable ions, either by ionizing a gas injected in the source, or by surface-ionizing the alkali naturally present on the filament surface. The injection into the Penning trap requires a bunched and cooled beam, mostly to optimize the transmission efficiency but also to reduce the phase-space volume when trapping the ions. For this purpose, a gas-filled Radio Frequency Quadrupole (called
GPIB for General Purpose Ion Buncher) is also developed at CENBG. The GPIB will be installed on the entrance
beam line of the DESIR hall, acting as the main cooler-buncher of DESIR. Details on this device will be found in
[42]. As displayed in Figure 2, the PIPERADE setup is placed directly downstream of the GPIB. At its final position
at DESIR/GANIL, PIPERADE will be displaced in parallel to the GPIB and the main beam line. Ion bunches will
thus be sent to PIPERADE via a transfer line equipped with two 90° electrostatic deflectors. One of these electrostatic
deflectors has been constructed and installed at CENBG (see Figure 2) between the GPIB and PIPERADE devices for
test purposes (e.g. transverse and longitudinal emittance measurements).

As can be seen in Figure 2, the different devices are held on separate platforms electrically floated with respect to 214 the ion source potential of 30 kV. The difference of the GPIB and PIPERADE platforms to the main source platform 215 is tunable via 0 - 400V power supplies (DELTA Electronika SM1500) with negative polarity, one dedicated to each 216 platform. This allows to adjust the ion energy for an optimized injection in the devices (about 29.9 kV for the GPIB 217 and about 29.95 kV for PIPERADE). The transfer line from the GPIB to the PIPERADE setup through the deflector 218 is floated at 27 kV, to be in the same electrostatic configuration as in DESIR where the 3-keV ions will be deflected. 219 The ions extracted from the Penning-trap system are then accelerated to almost 30 keV and sent to a detection system 220 dedicated to tests or mass measurements. In the future, the ion bunches will be sent back to the main DESIR beam 221 line via a 45° bending. 222

Different beam optics systems are used to control the shape and the position of the beam all along the beam line: a 223 DESIR quadrupole triplet is located between the source and the GPIB to optimize the injection into the GPIB and an 224 einzel lens is located downstream the GPIB for an optimum injection of the beam into the magnetic field of PIPERADE. 225 In addition, sets of horizontal and vertical steerers are located upstream of both GPIB and Penning-trap devices, in order to correct the angle and position of the ion beam. As can be seen in Figure 2, retractable beam profile monitors 22 are used to monitor the radial distribution and position of the ion beam injected in the GPIB and PIPERADE setups. 228 Three Faraday cups along the beam line are used to optimize the ion beam transmission efficiency in continuous mode. 229 When bunched with the GPIB, the ions are detected by micro-channel plates (MCP) detectors behind the GPIB at 27 230 kV and behind the traps at ground potential. The different beam diagnostics and their electronics are described in detail 231 in Section 4.3. The whole PIPERADE beam line, starting after the deflector, composed of DN160 crosses, bellows and 232 a DN125 vacuum tube inserted into the magnet, use the CF standard and a very low magnetic susceptibility stainless 233 steel (316L-1.4435). Two magnetically-levitated turbomolecular pumps (Edwards STP-1003) are located at both ends 234 of the setup, far from the magnet axis, as are the vacuum gauges. A third pump (Edwards STP-A803C) is located below 235 the MCP chamber after the trap system. The pressures at the injection and extraction sides, are  $8 \times 10^{-8}$  mbar and 1 236  $\times 10^{-8}$  mbar, respectively. The injection side pressure is higher because of the GPIB helium gas. It will be lower at 237 DESIR because the GPIB will be further upstream and additional pumping systems will be installed on the deflector 238 chambers. As it will be mentioned later, this pressure is higher when injecting He gas in the first trap. The pressure at 239 the MCP chamber is of the order of  $10^{-8}$  mbar. 24

# **4.** Technical description of the Penning-trap system

# 242 4.1. Double Penning trap

The double Penning trap of PIPERADE is shown in Fig. 1. As mentioned before, with a radius of 32 mm, the purification trap is one of the largest Penning trap installed at any RIB facility (see [43] for details on the 90mm-radius Penning trap of the TAMUTRAP facility), whereas the measurement trap has a radius of 10 mm. For both traps, deviations from the ideal quadrupole field are compensated by correction electrodes added between the rings and the endcaps electrodes. In addition, the dimensions of all electrodes and the voltages applied on them have been calculated to limit the anharmonicities of the electric trapping potentials (see Tables 1 and 2).

As can be seen in Figure 1.a), the endcaps of the purification trap are 4 times axially segmented, to offer the 249 possibility to apply DC gradients at the injection and the extraction of the ions. In trapping configuration, they are all 250 at the same potential. In the radial direction, as can be seen in Figure 1.b), the purification trap and the measurement 251 trap have an 8-fold and 4-fold segmented central ring electrode, respectively, allowing to apply RF excitations. The 252 correction electrodes are also radially segmented (two parts) for implementing a broad-band Fourier-Transform Ion-253 Cyclotron-Resonance (FT-ICR) detection [44], allowing a quick broad identification of the highly-abundant trapped 254 contaminants. Filters and pre-amplifiers boards are directly mounted on the trap structure inside the vacuum, in order 255 to reduce the noise of the very small induced current signal picked up on the electrodes. The full electronics system has 25



**Figure 3:** Top: Trap tower in the superconducting magnet consisting of injection/extraction optics and the double Penning trap separated by a diaphragm and entrance/exit beam optics on both sides of the magnet. Bottom: Magnetic field in Tesla along the trap tower.

been designed and built by Stahl-Electronics [45]. This detection technique has not been commissioned yet. Different 257 diameters for the diaphragm have been machined in order to test different excitation patterns. The presently installed 258 one has a 4 mm diameter. In addition, adaptation electrodes (see Figure 1.a) are added on both sides of the double 259 Penning trap, in order to fix the optics electrodes towers, which have a different diameter than the traps. As mentioned 260 earlier, the double Penning trap will be used in different configurations, which require He buffer gas, in one and/or the 261 other trap. For that reason, the gas feedings to both traps are independent and consist of PEEK tubes connected to the 262 adaptation electrodes via gas inlets, made of brass. Outside the vacuum, stainless steel gas tubes allow to transfer the 263 gas from the two mass flow controllers (BROOKS SLA5850S) to the gas feedthroughs. With the present diaphragm 264 diameter of 4 mm, when injecting He gas in the first trap, the pressure upstream the magnet measured by the gauge 265 can be increased up to about  $5 \times 10^{-6}$  mbar without degrading the vacuum downstream the Penning-trap setup. Monte Carlo simulations using the Molflow+ software [46] have been performed to estimate the pressure inside the first trap cavity when He gas is injected, under the assumption of being in a molecular regime. A factor of 12 between the 268 pressure measured by the gauge and the pressure inside the trap has been determined. 269

#### 270 4.2. Tower structure

The trap tower structure located in the superconducting magnet is divided into 3 independent parts: the double 271 Penning-trap structure and two sets of 10 and 11 cylindrical electrodes for the injection and the extraction of the ions, 272 respectively, in the critical areas of the magnetic field gradients (see Figure 3). On both sides of the double Penning 273 trap, the last injection electrode and the first extraction electrode are specific adaptation electrodes (see Figure 1.a), 274 with the same radius as the traps, to fix the optics electrodes, which all have a radius of 20 mm and 51 mm length. The 275 full tower has been designed and machined at the Max Planck Institut für Kernphysik (MPIK) in Heidelberg, Germany. 276 The measurement trap electrodes and the diaphragm are made of oxygen-free copper, chosen for its high con-277 ductivity and low magnetic susceptibility. All the injection, extraction and purification trap electrodes are made of 278 aluminum alloy (AW-5083), a compromise to have a reasonable weight, critical for a precise alignment and for an 279 easier assembly of the full structure. The aluminum electrodes have first been plated with a 5- $\mu$ m copper layer, and all 280 the electrodes have then been silver (15  $\mu$ m) and gold (5  $\mu$ m) plated. The gold layer is to prevent oxidation whereas the 281 silver one prevents gold from diffusing into the copper material. In general, a tolerance of  $\pm 30 \,\mu$ m has been achieved 282 for the dimensions of all the electrodes. All electrodes are insulated from each other by MACOR<sup>®</sup> rings. The tower 283 electrodes are designed in such a way that the insulator rings cannot be seen by the ions (see Fig.1.a). Concerning the 284 radially-segmented electrodes, the segments are insulated from each other by saphire balls of 1.5 mm diameter. The 285 kapton-insulated wires are connected to each electrode with M2.5 titanium screws. This tower is inserted in a DN125 286 vacuum tube and held via three rods screwed on metal landmarks soldered on the flanges at each extremity of the tube. 287 Since the tower is thus radially and axially self-aligned in the tube, the latter can then be aligned in the magnet thanks 28

Electrode	Length (mm)
Purification trap $(r = 32 \text{ mm})$	
Endcap 1 (PE1)	30.0
Endcap 2 (PE2)	17.5
Endcap 3 (PE3)	17.5
Endcap 4 (PE4)	30.0
Correction 1 (PC1)	25.1
Ring (PR)	9.310
Correction 2 (PC2)	25.1
Endcap 5 (PE5)	30.0
Endcap 6 (PE6)	17.5
Endcap 7 (PE7)	17.5
Endcap 8 (PE8)	30.0
Diaphragm $(r = 2 mm)$	30
Measurement trap ( $r = 10 \text{ mm}$ )	
Endcap 1 (ME1)	29.7
Correction 1 (MC1)	7.185
Ring (MR)	2.224
Correction 2 (MC2)	7.185
Endcap 2 (ME2)	29.7

Table 1

Dimensions (in mm) of the trap electrodes. The electrodes are separated from each other by a gap of 1 mm.

to screws from a special system fixed to the magnet in vertical and horizontal directions. The radial alignment will
be described in section 4.6.3. In addition to the main trap tower, two other 10-electrode towers are installed on each
side of the superconducting magnet, in the regions of deceleration/acceleration of the ions, and were also designed and
manufactured at MPIK. They are made of aluminum alloy and have a radius of 20 mm and 60 mm length.

#### **4.3.** Beam diagnostics and detectors

Monitoring the ion beam is crucial to optimize the beam line and the in-trap techniques. As the trap device is 294 on a high-voltage platform, there is no pulsed drift tube, the transmission efficiency can thus be optimized with a 295 continuous beam along the whole beam line. To do so, three movable Faraday cups (FC) are installed in the beam line, 296 as can be seen in Figure 2. These are DESIR-standard FC developed by GANIL, covering a very wide range of current 297 intensities, from only 50 fA to 100  $\mu$ A. To achieve such a high sensitivity, each FC is coupled to a low-bandwidth 298 transimpedance linear amplifier called PicoLIN [47], also developed by GANIL within the SPIRAL2 project. The 200 beam position, size and shape is monitored with SPIRAL2 beam profile monitors (BPM), based on secondary electron 300 emission of 47 tungsten wire harps (0.5 mm step) for both horizontal and vertical planes [48]. Equipped with high-301 sensitivity charge preamplifiers, these semi-interceptive BPM are used to monitor down to a few tens of pA ion beams 302 with a transparency higher than 90%. 303

Ion bunches generated by the GPIB can be detected by the FC, coupled to a fast commercial I/V converter (FEMTO 304 DHPCA-100). This detection system can be used only for high-intensity bunches (> 10<sup>4</sup> particles in a 1  $\mu$ s bunch), 305 the lower ion number limit strongly depending on the time distribution of the bunch. The voltage image of the bunch 306 intensity is digitized with a Red Pitaya board, which is also controlling the amplifier using digital I/O (switchable gain 307 from  $10^2$  to  $10^8$  V/A). The Red Pitaya board is a cost-efficient data acquisition platform based on a Xilinx FPGA and 308 a dual-core ARM processor running a Linux operating system. Amplifier output signal sampling and quantization are 309 achieved with a 14-bit ADC at 125 MSample/s in parallel with the digital I/O processing without any dead time. The 310 Australian Synchrotron EPICS driver support is used to run the Faraday Cup EPICS server (see section 4.5) in the Red 311 Pitaya itself [49]. 312

In case of low-intensity bunches, there are two MCP's (Topag MCP-MA33/2) installed in the beam line, one after the GPIB and one after the Penning-trap setup. They allow measuring the absolute number of ions in a bunch as well as performing time-of-flight measurements. The MCP anode signal is discriminated and a specific counting system has been developed. This FPGA development called RedPiTOF has been implemented into a dedicated Red Pitaya. Thanks to the use of two digital inputs (MCP counts and bunch gate signals), it allows to benefit from 50 MHz counters, time measurements with 10 ns time resolution and TOF spectrum construction in 16k channels without any dead time.

The modified embedded EPICS server (see section 4.5) allows from any EPICS Client to monitor online the MCP counting rate, the number of counts per bunch and the TOF spectrum. More details about this new development will be presented in a dedicated paper, under preparation.

A position-sensitive MCP (delay-line detector) is planned to replace the MCP after the trap, in order to implement the phase-splitting [21, 22] and PI-ICR [20] methods described in section 2.2.

# **324** 4.4. Trap electronics

In order to meet the DESIR High Voltage-Power Supplies (HV-PS) requirements, ISEG multichannel crates are 325 used for providing the DC voltages to the DESIR instruments. The reasons of such a choice are (i) the large variety of 326 low-noise, precise and stable HV-PS proposed, (ii) its ability to concentrate a large number of HV channels in a single 327 crate, and (iii) the CC-24 ISEG crate controller with its built-in EPICS server (see section 4.5). A SPIRAL2-like EPICS 328 records database is developed and used on all DESIR ISEG crates. The PIPERADE electronics stands in a dedicated 329 19" rack placed on a 29.95 kV platform and require 75 HV-PS, all with negative polarity. The DC signals for the trap 330 electrodes and the diaphragm are provided by 0 - 500V high-precision supplies (ISEG EHS-F205N). The injection and 331 extraction electrodes are supplied by 0 - 1kV modules (ISEG EHS F010n) whereas the entrance and exit electrodes on 332 both sides of the magnet are supplied by 0 - 6kV modules (ISEG EHS F060n). The switching of the trapping potentials 333 is required to be fast, in order to capture efficiently the ions and to extract them from the traps without degrading their 334 energy distribution. This is performed by homemade fast switches (see [42] for more details), capable of switching up 335 to 100 V in about 30 ns. The RF fields for the different motion excitations are supplied by Agilent 33510B function 336 generators with a 1  $\mu$ Hz frequency resolution. The ring electrode of both traps being supplied by both RF and DC 337 signals, AC/DC couplings are performed before the connection to the trap electrodes. Another main instrument used 338 as the conductor of the traps has been developed on a National Instruments CompactRIO device: the Pulse Pattern Generator (PPG). This real-time and FPGA-based device triggers the function generators and the fast switches with 340 respect to a given time pattern defined by the users with a 12 ns time resolution. Ion bunch injection, trapping, cooling 341 and excitation times, ion bunch transfer and extraction are controlled by this PPG. 342

# **4.5.** Control system

Control System (CS) developments performed at CENBG for DESIR are based on the Experimental Physics and 344 Industrial Control System (EPICS) architecture [50], being the basic framework for the SPIRAL2 control system [51]. 345 PIPERADE is therefore also fully remotely controlled under EPICS. This system is based on Clients (Operator Inter-346 faces) and Servers (Input Output Controllers IOC) communicating together via shared Process Variables (PVs) on an 347 Ethernet Network using a dedicated communication protocol named Channel Access (CA). Most of the PIPERADE 348 electronics is embedded on a high-voltage platform. Therefore, fiber optics coupled to Ethernet switches ensure gal-349 vanic insulation and TCP communication of the equipment with the EPICS IOCs running on a CentOS Linux PC. Some 350 IOCs are embedded into the equipment: this is the case for the ISEG HV multichannel crate (ISEG CC24 Controller) 351 and the Red Pitaya used for beam intensity, ion counting and time-of-flight (RedPiTOF) measurements. SPIRAL2 352 vacuum systems and interlocks are controlled using dedicated PLCs (Siemens S7-1500). The Profibus Fieldbus is 353 used by the vacuum PLC to communicate with turbo-molecular pumps and Profinet (Profibus on Ethernet Network) is deployed to manage Input-Ouput terminal modules (ET 200S) distributed along the beam line and on the high-voltage 355 platforms. Each PLC has its own HMI (Human Machine Interface) on a dedicated Touch Panel. 356

Shared software development tools are used such as the SPIRAL2 version of CSS/BOY (CSS-Dev) used to build most of the Graphical User Interfaces (GUIs) and will handle central services like the data archiver or the alarm handler system in the near future. EPICS with its CA protocol makes possible to monitor and control any beam line equipment through its PVs in many programming languages. Using this EPICS feature, a Python program is under development to operate the traps, i.e. scan the different trapping and excitation parameters, control the PPG and read on-line output data from the RedPiTOF instrument. Bunch counts and TOF spectra are processed and plotted as a function of the scanned parameters. It is inspired by the PyMassScanner program [52] developed at JYFLTRAP.

# **4.6.** Superconducting magnet

The superconducting magnet is a 7-Tesla magnet manufactured by CRYOGENIC [53], consisting of a set of NbTi windings immersed in liquid helium at 4.2 K. The main magnet has a 160 mm room-temperature bore in which the vacuum tube is installed and a cryostat with an overall diameter of 1112 mm and a length of 1250 mm. It has a 500

liter helium reservoir suspended within the cryostat vacuum space by stainless steel necks attached inside the turrets, 368 surrounded by a 125 liter annular nitrogen reservoir. The main coil has been loaded to 118 A, leading to a magnetic 369 field of 7 Tesla. There is also an independent active shield coil wound onto the main winding magnet where no current 370 is applied. However, a low current created by inductive coupling to the main coil is increasing with time, and might 371 slightly modify the magnetic field. Therefore, every few months or before a precision measurement, the current on this 372 coil has to be released. Two other superconducting compensation coils connected to the main coil, i.e. with the same 373 current, are positioned on both ends of the magnet, allowing a first rough compensation of the inhomogeneity along the magnet axis. In addition, there are two sets of superconducting shim coils, allowing to adjust independently the 375 homogeneity over two specific regions separated by 20 cm, corresponding to the two trap regions. Each set of coils 376 has three 1st-order shim coils in the three directions X, Y and Z and an additional 2nd-order shim coil in Z direction 377 (magnet axis) to compensate non-linear inhomogeneities. 378

#### 379 4.6.1. Field homogeneity

The field homogeneity in the trapping region is crucial because the radial motion frequencies as well as the true 380 cyclotron frequency depend on the magnetic field. As ion motions have non-zero amplitude, any inhomogeneity of 381 the field in the space where the motions take place leads to frequency shifts, resulting in a loss of resolving power in 382 mass separation or precision in mass measurements. The shimming has been done by adjusting currents of the order 383 of a few ampere on X and Y shim coils for radial shimming, and on the Z shim coil for axial shimming. The 2nd-order 384 coils were finally not needed for the adjustment. Since the latter have a strong inductive coupling to the main magnet, 385 having in principle no current on these shim coils allows us to release from time to time, as for the shield coil, the 386 accumulated induced current. An NMR probe coupled to a precision teslameter (Metrolab PT2025) has been used 387 to precisely measure the magnetic field along the axis and around the two trap center regions. Figure 4 shows the 388 magnetic field homogeneity, i.e. the relative deviation from the centers of the trapping regions, separated by 20 cm. A 380 wider region is shown for PT (purification trap), which has larger dimensions, and where ions will move further from 390 the trap center. Even over a very large region of 10 mm radius and 20 mm length the homogeneity is still of the order 391 of 3 ppm. On the MT (measurement trap) side, an homogeneity below 1.3 ppm has been obtained over a region of 5 392 mm radius and 10 mm length. 393

One should note that with the NMR-probe installed in the vacuum tube, the homogeneity determination was performed without the trap electrodes inserted in the tube. However, as it is described in Section 4.1, all materials were carefully chosen to be of very low magnetic susceptibility, so as not to induce any additional field inhomogeneity.

# 397 4.6.2. Field drift

Due to the so-called flux creep phenomenon [54], the magnetic field decreases over time. The active shield coil 398 allows to reduce this drift from 0.13 ppm/h to 0.04 ppm/h. However, for precision mass measurements, this drift is still 399 too high. Therefore, an additional warm coil has been added afterwards in the magnet bore, allowing to compensate 400 very precisely the linear drift by applying a ramp of the order of  $\pm 100 \,\mu$ A/h. This has been tested with the NMR-probe 401 located at the center of the measurement trap's region and showed that the field drift can be reduced by about two 402 orders of magnitude, as can be seen in Figure 5. Due to the limited precision of the NMR-probe and the sensitivity of 403 the teslameter to temperature fluctuations, this will have to be determined more precisely with the cyclotron frequency 404 of trapped ions. 405

# 4.6.3. Tube alignment with respect to the magnetic field

Another cause of ion frequency shifts is a misalignment between the electric trapping field and the magnetic field axes. The way the main coil is suspended in the cryostat does not guarantee a perfect alignment of the coil in the main magnet structure. The coil also slightly moves when cooling the magnet, therefore the alignment procedure has to be performed when the magnet is warmed up and cooled again, i.e. after the move of the setup to GANIL.

The trap electrodes are mechanically aligned in the vacuum tube but this assembly must be aligned with the magnetic field axis. The option to move the vacuum tube with respect to the magnetic field axis has been chosen. It prevents moving the magnet while it is cold, which can be risky.

A standard procedure using an electron-gun device inserted in the vacuum tube has been used (see Figure 6). By heating a tungsten ribbon positioned at the center of the magnet with a current of 10-15 A and by floating it to a potential of about -50 V, low-energy electrons are created and thus spiral closely around the magnetic field lines on both sides of the magnet. Two plates with apertures of 0.5 mm diameter each fixed on both sides of the filament and



**Figure 4:** Relative azimuthal magnetic field deviation from the centers of the PT (purification trap) and MT (measurement trap) trapping regions. The centers of these regions are at r = 0, z = -10 cm and z = +10 cm, for the PT and MT regions, respectively. Deviations are shown for different azimuth angles at a radius of 10 mm and over 20 mm length for the PT region and at a radius of 5 mm and over 10 mm length for the MT region. For both regions, the red bold lines correspond to the axial centers of the trapping regions.

at a distance of 15 mm, define the initial shape and size of the electron beam. Detectors are placed at both ends of the 418 magnet, each of them consisting of a metallic plate acting as a Faraday cup on which another 8-fold segmented plate 419 (4 inner quadrants surrounded by 4 outer ones) with a 0.5 mm pinhole in the center is fixed. The aim of the procedure is to move the vacuum tube in such a way that the electron beam travels through the pinhole in the first layer of the 421 detector and thus the electron current on the main detection plate is maximized. The segments of the first plate allow 422 to estimate the position of the beam. The further the detectors are from the filament, the more precise is the alignment. 423 However, starting the procedure with very far detectors is not convenient if the beam is not observed at all. Therefore, 424 the two sets of detectors were mounted on elements sliding on rods, such that the axial position of the detectors could 425 be controlled by a crank from outside the vacuum (see Figure 6), so that the setup does not have to be opened every 426 time the position has to be changed. 427

The vacuum tube inclination was finally corrected by 2.7(13) mrad. It is thus not perfectly aligned with the rest of the beamline anymore, but now well aligned with the magnetic field axis. The resulting cyclotron frequency shift from the possible remaining angle can be calculated from the formula given in [55, 56]:

$$\Delta \nu_c = \frac{9}{8\pi} \nu_- \theta^2 \tag{2}$$

with  $\theta$  the angle between the electric and magnetic field axes and  $v_{-}$  the magnetron frequency of the trapped ions, being expressed, in first-order approximation, as  $v_{-} = U_0/(4\pi d^2 B)$ . One can notice from the Equation 2 that the absolute frequency shift is, in first-order, mass-independent. As explained in the following section, the trap parameter  $d^2$  can be determined from the simulated electric field and is equal, for the measurement trap, to 134.49 mm<sup>2</sup>. With  $\theta = 1.3$  mrad, corresponding to the uncertainty on the angle, the resulting cyclotron frequency shift in the second trap will be from 0.5 mHz for a trapping potential of 10 V, to 5 mHz for a trapping potential of 100 V. The relative uncertainty on the true cyclotron frequency  $v_c$  depends then on  $v_c$  itself, the heavier the mass the larger the uncertainty. However, as it is explained in Section 2.2, the cyclotron frequency of an ion of interest  $v_c$  is always measured relatively to a well-known reference ion with a cyclotron frequency  $v_c^{ref}$ . Therefore, the resulting relative uncertainty we are interested in is the



**Figure 5:** Magnetic field B relative to the initial magnetic field B0 as a function of time. The red lines correspond to a fit of the data to a linear function ; the resulting slope is shown on the Figure. Top: No current is applied on the additional warm coil. Bottom: A positive ramp current is applied on the warm coil.



**Figure 6:** Electron gun device installed in the vacuum tube, consisting of a tungsten ribbon in the center, apertures on both sides, as well as 8-fold segmented detectors with a hole and a plate behind. A crank connected to a worm gear is used to change the axial position of the detectors with respect to the filament.

one on the ratio  $r = v_c / v_c^{ref}$ . In [56], it is given by the formula:

$$\frac{\delta r}{r} = \frac{9}{4} \theta^2 \frac{v_-}{v_+^{ref}} \left( \frac{v_+^{ref} - v_+}{v_+} \right) \tag{3}$$

By assuming that  $v_+ \approx v_c$  for both the ions of interest and the reference ions, one can simplify the Equation 3 and define a shift factor *R* depending only on the trap parameters, the magnetic field strength and the misalignment of the magnetic field to the trap axis. For a mass measurement, the relative uncertainty will then be given by the trapping potential  $U_0$  and the mass difference between the ions of interest and the reference ions  $\Delta A$ :

$$\frac{\delta r}{r} = R \cdot U_0 \Delta A = \frac{9}{4} \theta^2 \frac{1}{2d^2 B^2} \frac{u}{q_e} \cdot U_0 \Delta A \tag{4}$$

with u the atomic mass unit and  $q_e$  the elementary charge (assuming all trapped ions are of 1<sup>+</sup> charge state). The final

Electrode	Voltage(V)
ENT01 - ENT10	from -2950 to -1000
INJ01 - INJ10	from -800 to -85
Purification trap	Open/Closed
Endcap 1 - Endcap 4 (PE1 - PE4)	-84 / 0
Correction 1 (PC1)	-82 / -70
Ring (PR)	-80 / -80
Correction 2 (PC2)	-82 / -70
Endcap 5 - Endcap 8 (PE5-PE8)	-84 / 0
Diaphragm/Measurement trap	from -85 to -90
EXT01 - EXT11	from -100 to -120
OUT01 - OUT10	from -130 to -3000

#### Table 2

Voltages (V) applied to the entrance electrodes (ENT01-ENT10), the injection electrodes (INJ01-INJ10), the extraction electrodes (EXT01-EXT11) and the exit electrodes (OUT01-OUT10). For the purification trap, voltages (V) applied in "opening mode", i.e. when the ions are either injected in the trap (voltages from PE1 to PR) or extracted from the trap (voltages from PR to PE8), and in "closed" mode, i.e. when ions are trapped. The setup and the power supplies are installed on a high-voltage platform. All these voltages are thus relative to the platform reference.

relative uncertainty resulting from an angle of 1.3 mrad between the magnetic and electric field axes is:

$$\frac{\delta r}{r} = 3.0 \times 10^{-12} V^{-1} \cdot U_0 \Delta A \tag{5}$$

Even with a trapping potential  $U_0$  of 100 V and a  $\Delta A$  of 10, the relative uncertainty of  $3.0 \times 10^{-9}$  is still negligible on the level of the expected precision of the Penning trap, i.e. of the order of  $10^{-8}$  for short-lived ions.

#### 430 5. First offline tests with the purification trap

We report here the first offline tests of the PIPERADE mass spectrometer. As no gas was injected in the stable ion source, the ion beam consisted only of surface-ionized elements. The ion beam was first cooled and bunched by the GPIB, with RF parameters set to transmit light ions, such as  ${}^{39}K^+$  or  ${}^{40}Ca^+$ , and then sent to the PIPERADE traps. A so-called beam gate was implemented using one of the steerers at the exit of the ion source. Switching this electrode for a short moment allows to inject in the GPIB a well-defined number of ions, and also to avoid the GPIB to be fed constantly with "hot" ions that mix with the cold ones when extracting an ion bunch.

The ion bunches are extracted from the GPIB floated at 29.9 kV towards the deflector at 27 kV with an energy of 437 about 2.9 keV, and are then sent to the Penning-trap platform, which is at 29.95 kV. In order to attenuate the strong 438 defocusing effect of the platform voltage change from 27 kV to 29.95 kV and a abrupt drop of the ion energy, the 439 first entrance electrodes are set at about -2950 V, and then a smooth gradient is applied, in order to decelerate the ions 440 for the injection in the purification trap, where the ion energy has to be lower than the trapping potential, in this case 441 80 V. Table 2 shows the voltages applied on the different electrodes. For the purification trap electrodes, "Open" and 442 "Closed" correspond to the settings for injection/extraction and trapping modes, respectively. For the first tests, the 443 four axial segments of each endcap were all connected together. 444

Before performing any trapping in the purification trap, the bunches were shot through the Penning trap tower and 445 detected on the MCP detector behind the setup. The absolute transmission efficiency through the trap device is difficult 446 to determine, because the MCP's before and after the traps have not been precisely calibrated and despite the fact they 447 are identical, they might have slightly different detection efficiencies. This is mostly due to different time and spatial 448 distributions of the bunches hitting the detector leading to different saturation effects, but also due to the difference in 449 ion energy (3 keV after the GPIB and 30 keV after PIPERADE) and the fact that there are grids in front of the GPIB 450 451 MCP (to measure the bunch energy dispersion) which might impact the detection efficiency. A test bench with another offline ion source is being mounted in the hall of CENBG, in order to precisely calibrate the detectors, depending on 452 the ion beam conditions. Despite the difficulty of precisely determining the efficiency, the number of counts/bunch 453 detected on the MCP after the GPIB and on the one after PIPERADE were similar for a given beam gate duration, 454 which shows that the overall transmission efficiency is excellent, most probably above 30-50%. One should note that 455

in continuous mode, by detecting the beam on the Faraday cups, the transmission efficiency through the traps has been
 estimated to about 60-70%. All these efficiencies will more precisely be measured during the on-going commissioning.

The trapping mode has then been tested. In order to capture the ions coming from the GPIB, the injection endcaps (PE1-PE4) are open while the extraction endcaps (PE5-PE8) are kept closed. Then, when the ions reach the trap center,

- (PE1-PE4) are open while the extraction endcaps (PE5-PE8) are kept closed. Then, when the ions reach the trap center,
   the injection endcaps have to be closed, i.e. switched up to 0 V. The capture efficiency can be determined by the ratio
- of the number of counts of the MCP detector after a trapping cycle to the number of the counts in "shooting-through"
- mode, i.e. without any trapping. This has been determined to be >80% and is reliable because the MCP detector is the
- same one for both measurements.
- The first sideband buffer gas cooling technique was performed with the following time pattern:
- 1) Extraction from the GPIB (triggers the PPG of the trap)
- <sup>466</sup> 2) Waiting time while the ions fly from the GPIB to the PT (62  $\mu$ s)
- **3)** Closing of the injection endcaps and first correction electrode
- 468 4) Axial cooling time (200 ms)
- **5)** Dipolar magnetron excitation (15 ms)
- 6) Quadrupolar cyclotron excitation (200 ms)
- 471 7) Waiting time for cooling (200 ms)
- 8) Opening of the extraction endcaps and second correction electrode
- 473 9) Trigger for the MCP detection gate
- 474

Ars As can be seen from the above time pattern, after the capture of the ions, a waiting time is needed to axially cool the ions before applying the magnetron excitation. This time is strongly dependent on the amount of buffer gas injected in the trap, the higher the pressure the shorter the time.

The magnetron excitation was first tested, meaning that step 6 was omitted. The dipolar field was applied during 10 magnetron periods with an amplitude of 2.2 Vpp. Figure 7 shows the number of counts/bunch detected on the MCP detector behind the trap as a function of the frequency of the RF excitation. We can see that at the resonance frequency  $v_{-}$ , the counts/bunch drops to zero because the ion's magnetron radius has been increased to an orbit higher

- than the diaphragm radius, and thus no ions can be extracted from the trap. The amplitude of the magnetron excitation
- was tuned, so that it is high enough to radially push the ions beyond the diaphragm, but low enough so that the ions are not too far from the center. The further they are, the harder it is to re-center them because of frequency shifts
- induced by anharmonicities of the electric field and inhomogeneities of the magnetic field. The magnetron frequency
- has been determined to be about 660 Hz. This is in perfect agreement with the magnetion frequency calculation from
- the formula  $v_{-} = U_0/(4\pi d^2 B)$ , with  $d^2 = 1360.90 \text{ mm}^2$  determined from a linear fit of the trap electric field simulated
- by SIMION [57] (see Eq. 1). The geometric formula for the characteristic trap parameter  $d = \sqrt{z_0^2 + r_0^2/2}$  is actually

<sup>489</sup> not correct anymore for a real cylindrical Penning trap. All these offline tests were performed with He gas injected

in the trap, giving a pressure of  $2.6 \times 10^{-7}$  mbar on the injection side of the magnet. From the Molflow simulations



**Figure 7:** Number of counts/bunch detected on the MCP detector behind the trap as a function of the frequency of the dipolar magnetron excitation.



**Figure 8:** Number of counts/bunch detected on the MCP detector behind the trap as a function of the frequency of the quadrupolar RF excitation. At the resonance frequency  $v_c$ , <sup>39</sup>K<sup>+</sup> ions are centered in the trap. The gaussian fit to the data, shown in red, has a sigma of 11.0 Hz

described in Section 4.1, the pressure inside the trap cavity was then of the order of  $3 \times 10^{-6}$  mbar.

A quadrupolar excitation of 200 ms duration was then applied (step 6 in the above time pattern) with 2 Vpp 492 amplitude, in order to re-center the ions. Figure 8 shows the number of counts/bunch detected on the MCP detector 493 behind the trap as a function of the quadrupolar excitation RF frequency. This first resonance allows to confirm that 494  $^{39}$ K<sup>+</sup> ions are indeed produced from the ion source. The resonance curve was fitted with a Gaussian function, resulting 495 in a sigma of 11.0 Hz. With a FWHM of about 26 Hz, the resolution  $v_c$ /FHWM is then 106 000. The targeted resolution 496 of this technique has thus been achieved. Studies are on-going to investigate the evolution of the resolution and the 497 re-centering efficiency with respect to the different excitation parameters. The magnetron and cyclotron excitation 498 amplitudes, as well as the amount of gas and the different pattern step times are strongly correlated and they all affect the sideband buffer-gas cooling performances. The next step is then to study separation performance as a function of 500 the total number of trapped ions and for different ratios between the ions of interest and the contaminants. 501

# **502** 6. Conclusions and outlook

A double Penning trap has been developed for mass separation and mass spectrometry at the future DE-SIR/SPIRAL2 facility. The installation of this device at CENBG has been finalized and is now under commissioning. First offline tests using the purification trap have shown that a resolution of 10<sup>5</sup> can be achieved. The next main step is to implement the mass spectrometry and high-resolution separation techniques for the measurement trap of PIPERADE. The first on-line experiments at DESIR with PIPERADE are foreseen in 2026.

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# **Declaration of interests**

 $\boxtimes$  The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

⊠The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

