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The vacuum system of the Low Energy Ion Ring at CERN: Requirements, design, and challenges

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Abstract

For the heavy ion program at CERN's Large Hadron Collider, lead–lead collisions with a design luminosity of $10^{27}\,cm^{-2}\,s^{-1}$ are foreseen. This will be achieved after an upgrade of the ion injector chain where the Low Energy Antiproton Ring (LEAR) is currently converted into a Low Energy Ion Ring (LEIR). Avalanche-like heavy-ion induced molecular desorption, first observed at LEAR and systematically studied at CERN's Heavy Ion Accelerator (LINAC 3), is the major challenge to achieve the required average dynamic pressure of about 4×10^{-12} mbar in LEIR. The LEIR vacuum requirements, the technical design, the implementation of non-evaporable getter coatings and low-outgassing collimators, and the concept of ion-beam scrubbing are reviewed in this paper.

Keywords: Accelerator vacuum system; Beam lifetime; Cross sections; Heavy-ion desorption; Non-evaporable getter (NEG); Coatings; Collimator; Scrubbing

1. Introduction

During accelerator operation with heavy ions, large pressure rises have been observed at CERN [1,2], GSI [3,4], and BNL [5,6]. Ions, lost from the beam and striking the vacuum chamber wall, can desorb 10^4–10^5 molecules/ion. This effect increases the dynamic pressure and causes further ion losses, which can severely limit the achievable ion intensity and beam lifetime in an accelerator. Dedicated measurements of heavy-ion induced molecular desorption yields have been performed since late 2000 at CERN's LINAC 3, aiming to quantify the desorption effect and to find pragmatic solutions to overcome this potential limitation for the LEIR vacuum system [2,7,8].

2. LEIR vacuum requirements

For LEIR, the requested beam lifetime τ is 30 s. The lifetime due to charge-exchange of a heavy ion with the residual gas is given by

$$\frac{1}{\tau} = \beta \times c \times \sigma_{tot} \times n, \tag{1}$$

where β is the ion velocity, c the speed of light, σ_{tot} the total cross section, and n the gas density, which does not depend on the gas species. The gas density is given by

$$n \cong 7.242 \times 10^{24} \times p/T, \tag{2}$$

where the pressure p is measured in mbar and the temperature T in Kelvin. At 20 °C and 1 mbar one finds $n \cong 2.47 \times 10^{22}$ molecules/m^3. In a gas mixture, the product $\sigma_{tot} \times n$ in Eq. (1) must be replaced by the sum over all relevant gas species, i.e. by $\Sigma\sigma_i \times n_i$. Consequently, the beam lifetime can be expressed in the following way:

$$\frac{1}{\tau_{total}} = \frac{1}{\tau_{H_2}} + \frac{1}{\tau_{CH_4}} + \frac{1}{\tau_{CO}} + \frac{1}{\tau_{CO_2}} + \cdots. \tag{3}$$

To evaluate the LEIR vacuum requirements, we need to calculate the individual cross sections and gas densities for Pb^{54+} ions with an energy of 4.2 MeV/u ($\beta = 0.0943$). The charge-exchange of a heavy ion passing through a gaseous medium can be described by the capture and loss of electrons. To determine the electron-capture and electron-loss cross sections ($\sigma_{capture}$, σ_{loss}), formulae introduced by Franzke [9] were used. Table 1 summarizes the calculated cross sections, necessary gas densities, and the equivalent partial pressures for the requested 30 s beam lifetime in LEIR [10].

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Table 1
Electron-loss (σ_{loss}) and electron-capture ($\sigma_{capture}$) cross sections, the dynamic gas density (n) and corresponding partial pressures (p) for a 30 s beam lifetime of Pb^{54+} ions at 4.2 MeV/u in LEIR

Gas	σ_{loss} (cm^2)	$\sigma_{capture}$ (cm^2)	σ_{tot} (cm^2)	n (m^{-3})	p (mbar) at 20 °C
H_2	5.38×10^{-19}	1.58×10^{-17}	1.63×10^{-17}	$7.22\times10^{+11}$	2.92×10^{-11}
He	5.38×10^{-19}	1.58×10^{-17}	1.63×10^{-17}	$7.23\times10^{+11}$	2.93×10^{-11}
CH_4	2.66×10^{-18}	7.79×10^{-17}	8.06×10^{-17}	$1.46\times10^{+11}$	5.91×10^{-12}
H_2O	2.60×10^{-18}	7.63×10^{-17}	7.89×10^{-17}	$1.49\times10^{+11}$	6.03×10^{-12}
N_2	3.65×10^{-18}	1.07×10^{-16}	1.11×10^{-16}	$1.06\times10^{+11}$	4.29×10^{-12}
CO	3.64×10^{-18}	1.07×10^{-16}	1.11×10^{-16}	$1.07\times10^{+11}$	4.33×10^{-12}
Ar	4.09×10^{-18}	1.20×10^{-16}	1.24×10^{-16}	$9.50\times10^{+10}$	3.84×10^{-12}
CO_2	5.71×10^{-18}	1.67×10^{-16}	1.73×10^{-16}	$6.81\times10^{+10}$	2.76×10^{-12}

One can see that a dynamic pressure (in presence of a circulating lead ion beam) of 4×10^{-12} mbar N_2 equivalent will be necessary. Assuming H_2 is the dominant residual gas, a total pressure of 3×10^{-11} mbar would be sufficient for LEIR. A more realistic gas distribution has been measured during dedicated ion-induced desorption experiments at LINAC 3. It was found that the bulk of the molecules desorbed due to lead ion impact was CO [7,8]. CO_2 and H_2 were the second most abundant species in the desorbed gas. Taking measured values for the gas composition under heavy ion bombardment, an average dynamic pressure of $\approx 4\times10^{-12}$ mbar is necessary around the LEIR ring for $\tau = 30$ s [10]. An error bar for the dynamic pressure cannot be given because this value depends on the achievable gas composition during LEIR operation.

3. Vacuum system design

The LEIR vacuum system requires ultrahigh vacuum (UHV) technologies that had been developed at CERN for the Intersecting Storage Rings (ISR) and the Large Electron Positron Collider (LEP). In particular, a very strict choice of materials, vacuum pumps and instrumentation, cleaning procedures, and a sophisticated bakeout system are necessary to reduce the total dynamic outgassing rate to the 10^{-13} mbar $\ell\,s^{-1}\,cm^{-2}$ range with a negligible amount of leaks.

3.1. Vacuum chambers and tanks

The LEIR vacuum chambers and tanks are made out of stainless steel AISI 316LN or 316L, most of them have been recovered from the former LEAR machine. Owing to the UHV requirements, a bakeable all-metal vacuum system with Conflat™ flanges is used for most machine elements. Wheeler flanges with silver-coated copper wire-seals were chosen for large diameter tanks like kickers and septa. All vacuum chambers and bellows were cleaned according to the CERN procedure [11] and subsequently vacuum fired at either 950 °C for 2 h or 600 °C for 24 h.

3.2. Pumping system, instrumentation, and bakeout

Since the dynamic vacuum is a challenge in LEIR, a very careful design of the distribution of pumps and vacuum diagnostics (gauges, residual gas analysers) has been undertaken. A scenario to put linear pumping in terms of non-evaporable getter (NEG) was considered for all parts of the LEIR machine and was implemented wherever possible. Standard and even special shaped vacuum chambers were coated with a 2 μm thick TiZrV film and kept under vacuum as long as possible before installation. The layout of the LEIR vacuum system is displayed in Fig. 1.

The vacuum system of the main ring ($\ell \cong 80$ m) with its injection ($\ell \cong 12$ m) and extraction ($\ell \cong 12$ m) lines is separated into five sectors using all-metal type valves. The evacuation from atmospheric pressure to about 10^{-8} mbar is carried out with mobile pumping groups consisting of an all-metal valve, a 200 $\ell\,s^{-1}$ turbo molecular pump backed with a 30 $m^3\,h^{-1}$ primary pump, and a control system. The same pumping groups are used for leak detection and during bakeout of a vacuum sector. About 90% of the injection and extraction vacuum chambers are coated with NEG. For the LEIR main ring vacuum system about 42% could be NEG coated. Sputter ion pumps (400 $\ell\,s^{-1}$, 60 $\ell\,s^{-1}$) and titanium sublimation pumps are distributed in the LEIR machine. The sublimators are only installed at places where a NEG coating was not feasible, e.g., in the four bending magnet vacuum chambers, the kicker and septa tanks.

For instrumentation, vacuum gauges with a low X-ray limit and low outgassing are the only option for LEIR. We have chosen the CERN-type Bayard-Alpert gauge, developed in the 1970s for the ISR vacuum system [12]. This gauge can reliably measure total pressures of about 1–3 $\times10^{-12}$ mbar. As an alternative, the modified Helmer gauge [13], providing a low pressure limit in the 10^{-14} mbar range, might be an interesting additional instrument for future LEIR vacuum applications. In addition, bakeable Pirani and Penning-type gauges are used to measure the vacuum during pumpdown and bakeout when the UHV gauges are still switched off. Residual gas analysers are