EPA BEAM-VACUUM INTERACTION ION CLEARING SYSTEM

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ABSTRACT

The CERN 600 MeV Electron Positron Accumulator (EPA), built as part of the LEP pre-injector, is equipped with a stainless steel vacuum chamber fully vacuum-fired at 950°C and partly Argon glow-discharged prior to installation. As a consequence, the initial dynamic pressure rise has been low from the beginning leading to good lifetime and performances. Moreover, 40 ion clearing electrodes of the button type are distributed all along the ring circumference. These electrodes are designed for minimum coupling with the beam and, hence, do not contribute significantly to the machine impedance. The EPA clearing system providing a transverse electric field of around 50kV/m should be powerful enough to clear ions up to a beam current of about 4 A at an emittance ratio of 10%. Although there is evidence of a remanent neutralisation, may be due to residual pockets of longitudinally energetic ions, this system has proved to be essential to reach similar performances with electrons as with positrons, in terms of maximum intensity stored, lifetime, emittance and beam stability.

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1. Summary

The CERN 600 MeV Electron Positron Accumulator (EPA), built as part of the LEP pre-injector, is equipped with a stainless steel vacuum chamber fully vacuum-fired at 950 °C and partly Ar glow-discharged prior to installation. As a consequence, the initial dynamic pressure rise has been low from the beginning leading to good lifetime and performances. Moreover, 40 ion clearing electrodes of the button type are distributed all along the ring circumference. These electrodes are designed for minimum coupling with the beam and, hence, do not contribute significantly to the machine impedance. The EPA clearing system providing a transverse electric field of around 50 kV/m should be powerful enough to clear ions up to a beam current of about 4 A at an emittance ratio of 10%. Although there is evidence of a remnant neutralisation, may be due to residual pockets or longitudinally energetic ions, this system has proved to be essential to reach similar performances with electrons as with positrons, in terms of maximum intensity stored, lifetime, emittance and beam stability.

2. Introduction

The accumulator and damping ring EPA has already been described in detail elsewhere1. Designed as a buffer between the electron–positron lines LIL and the proton synchrotron PS, particles have only to transit up to 20 seconds in alternate accumulation cycles. Therefore, the requirement of sufficient particle lifetime was a priori not difficult to meet, at least in terms of sufficiently low residual gas pressure (10^{-8} mbar), even taking into account the increase in gas load resulting from synchrotron radiation induced desorption. However, it was clear already at the design stage that ion trapping in the electron beam of this machine would be significant due to its small circumference (126 m) and the number of equally spaced bunches (8), yielding possibly a full average space charge neutralisation. It was also clear that this would have detrimental consequences on the particle dynamics and lifetime, such as ion induced large tune shifts and spreads, as well as coherent and incoherent resonances, affecting the accumulation rate and maximum intensity2.

An early review conducted on various schemes to minimize the average ion neutralisation led to the decision to equip the machine with ion clearing electrodes and to design a vacuum system based on UHV technology in order to obtain operating residual gas pressures in the low 10^{-9} mbar range without in situ bake out3.

The effort was also spent at the design stage to simplify the mechanical structure of these electrodes and to minimize their contribution to the machine impedance budget.

3. Vacuum system performance

A detailed description of the EPA vacuum system has been given elsewhere4. The machine, divided in 6 sectors by 6 metal valves, is pumped by 36 triode sputter ion pumps of 200 l/s nominal pumping speed yielding an average air linear speed at 10^{-8} mbar of 13 l/sec·1 m⁻¹ in arcs and 7 l/sec·1 m⁻¹ in the long straight sections.

The vacuum chamber is built of AISI 316 LN and 304 L stainless steels of high purity, and is water cooled. In the bending arcs to remove the rather modest dissipation of 80 W/m at 78 mA nominal circulating current arising from the synchrotron radiation.

Extremely low thermal outgassing rates are obtained with relatively short pump-down times, allowing for pressures in the 10^{-10} mbar range obtainable in less than 2 days, and an ultimate average limit pressure of a few 10^{-10} mbar after a few months of pumping, with more than 90% of H2 in the residual gas. This is to a large part attributed to the 950 °C, 2 h Vacuum Firing (VF) applied as the last bulk degassing and surface cleaning treatment, after chemical cleaning and before installation. In addition, all vacuum chambers of one of the 4 arcs (sector 2) have been submitted to an Argon Glow Discharge Cleaning (AGDC), followed by a 350 °C vacuum bakeout just before installation, this in order to compare the effects of Vacuum Firing and AGDC on the specific pressure rise with synchrotron radiation.

Since the machine startup in July 1986, EPA has operated at 500 MeV. The specific pressure rise DP/\; [mbar/\; mA] resulting from synchrotron radiation induced desorption has been more or less continuously recorded together with the residual gas composition. Figure 1 below gives the recorded DP/\; as function of the beam dose (the integral versus time of the beam current), a measure of the energy received by the chamber used to assess the cleaning effect.

From the specific pressure rise the number of molecules released on the chamber wall per incident photon has been estimated initially at 2 \times 10^{-4} a value lower than the better ones obtained with aluminium chambers by a factor of 10. This is attributed to the VF treatment applied as the last cleaning step5.

During this period, the typical residual gas composition of 70% H2-30% CO with beam did not vary significantly. The AGDC arc sector proved to be noticeably cleaner, other parts of the machine showing traces of heavier gas species (CO2,Ox4)2.

4. Beam lifetime

Among the various gas related phenomena influencing the lifetime of particles in EPA single coulomb scattering by the nuclei of gas atoms, particularly of heavy gas species such as CO, was calculated to be dominant compared to Bremsstrahlung5,2. Both loss processes impose an exponential beam current decay with an e-folding time defined as:

\[ \tau_B = (\sigma_p c N_{atom})^{-1} \quad (c \text{ the velocity of light,} \quad \sigma_p \text{ the atomic density}) \]

The cross section \( \sigma_b \) is a weak function of the particle relativistic factor \( \gamma \), while \( \sigma_b \) is inversely proportional to \( \gamma^2 \), thus giving large cross sections at the relatively low energy of EPA:

\[ \sigma_b = \frac{4 \pi r_0^2 2 \gamma^2}{(\gamma^2 - 1)^2} \quad (\text{with } r_0 \text{ the classical electron radius,} \gamma \text{ the residual gas atom number and} B \text{ the maximum scattering angle permissible without loss on the chamber wall}) \]

\[ W = \ln(\gamma/\delta_y) - 4.6 \quad \text{with } \delta_y/\gamma = 1% \]

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Table 2 below gives the relevant cross sections and lifetimes for 1 nanobar (gauge pressure) in EPA with 70 % H2 and 30 % CO:

<table>
<thead>
<tr>
<th>gas</th>
<th>true pressure (mbar)</th>
<th>σB(cm²)</th>
<th>σsc(cm²)</th>
<th>τB(hr)</th>
<th>τsc(hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H2</td>
<td>1.2 10^-9</td>
<td>2.6 10^-25</td>
<td>2 10^-24</td>
<td>460</td>
<td>60</td>
</tr>
<tr>
<td>C0</td>
<td>5.1 10^-10</td>
<td>5.7 10^-24</td>
<td>2 10^-22</td>
<td>50</td>
<td>1.4</td>
</tr>
</tbody>
</table>

(*) Note with our residual gas composition the C0 true pressure is half the machine average gauge pressure with circulating beam

CO obviously is by far the most offending gas specie, and single scattering is the dominant loss mechanism. During the early hours of beam cleaning with electrons, the synchrotron radiation induced pressure rise P is large at high beam currents (*1) compared to the machine base pressure Po:

\[ P = Po \cdot \lambda \cdot I \]

such that with

\[ N_{atom} = k \cdot P \quad \text{[with } k=6.44 \times 10^{16} \text{ atoms per mbar and per cm}^{-2} \text{ for a diatomic gas]} \]

the product

\[ \tau_s = \frac{K}{P \cdot \lambda} \quad \text{[with } K = (\sigma \cdot c) \cdot \lambda \text{ mbar}^{-1} \cdot \text{hr}^{-1} \] (1)

\[ \tau_s = \frac{K}{P \cdot \lambda} \quad \text{for } \lambda \cdot I \gg Po \] (2)

Figure 2 below shows measured values of electron beam beam lifetimes at high current, with clearing electrodes on, when the dynamic pressure rise was high and the product \( \tau_s \cdot I \) approximately constant. Also shown are calculated values assuming single scattering as the limiting case. \( \tau = I \) increases with increasing beam dose as the machine specific pressure rise \( \lambda \) decreases.

**BEAM CURRENT * LIFETIME (%hours)**  
**EPA at 500 Mev (electrons)**

![Figure 2](image2)

The CO pressure of EPA, i.e., without beam, is a strong function of the exposure history to synchrotron radiation with time constants between minutes and several hours. This stems from the fact that the synchrotron radiation induced desorption is not only instantaneous, but has a long-term exponentially decaying component. The slopes of the curves given above are compatible with CO scattering and base pressures measured shortly after exposure.

**5 Ion clearing system**

The ion clearing system consists of button type electrodes (O.D. 32 mm) mounted on an electrical feedthrough and placed at 40 locations around the ring.

![Figure 3](image3)

A negative bias voltage ranging from 0 to -6kV from one common power supply provides the extracting vertical electric field. To minimise mechanical complication and interference with other equipment, most of these electrodes are mounted above the pumping ports, opposite to the ion pump and close to bending magnets in arcs where the ion drift velocity is a minimum. Initially designed to provide an extracting field of 2 to 10 kV, thought to be sufficient to extract ions from a 70 mA nominal electron beam, these electrodes were originally made of stainless steel and positioned flush with the vacuum chamber wall to minimise coupling with the beam. In the course of machine commissioning, it quickly became evident that the extracting field was insufficient, and that the system needed upgrade. Calculations showed that if the minimum field to extract ions had to be equal to the beam space charge field for a given current (in 50 kV/m for 400 mA), not only the voltage had to be increased but also the electrodes had to be put closer to the beam. The electrodes were therefore redesigned, benefiting from a novel idea to minimise their coupling impedance with the beam.

**Metallic clearing electrodes act like a capacitive pick-up.** Depending on their loading condition (coaxial cable) they may exhibit at certain frequencies a considerable beam coupling impedance (Figure 5a)

![Figure 4](image4)

\[ S_{21} = \frac{Z}{Z+Z_c} \quad \text{EPA}
\]

\[ S_{21} = \frac{Z}{2Z_e} \quad \text{with RF filter}
\]

\[ S_{21} = 2 \quad \text{ceramic with resistive coating and RF filter}
\]

![Figure 5](image5)

**Clearing electrodes longitudinal impedance bench measurement**

9) metallic, 1)metallic with RF filter, 2) ceramic with resistive coating and RF filter
This effect can be strongly reduced if the coaxial cables for the DC voltage are connected via an RF filter containing a dielectric or magnetic material with strong RF losses (figure 5b).

However, a much better reduction is obtained if on top of it the interaction with the wakefield itself is minimised. It is known that for an electromagnetic wave, a resistive layer with a resistivity $\square_{\text{res}}=3.77 \Omega$ is transparent. Therefore, new electrodes were made of an alumina body, coated with a few $\mu$m thick resistive layer ($\square_{\text{res}}=30 \Omega$). The resistive material is a glass-metallic salts compound paste (series R 8400-HERAUS) normally used for thick film resistors in printed electronic circuits and fired at 850°C. After firing, the output properties of this material are comparable to stainless steel. In contrast to thin film technology (a few hundred metallic monolayers for high resistivity), these thick layers are much more stable against ion bombardement and vacuum epitaxy and can be produced for any value between 1Q and 10 MΩ. The impedance of these clearing electrodes is shown in fig: a 500 fold reduction compared to the metallic ones has been obtained. It can be seen that the total impedance of the 40 electrodes is negligible given that the impedance of the machine is $(Z/n)=20 \Omega$. This has been confirmed by measurements with the beam 10.

6 Performance of the clearing system: beam-ion interaction

The performance of the ion clearing system is judged through its on/off response on the adverse effects of ions on the beam (emittance blow up, transverse modes, beam stability, maximum intensity achievable), rather than through a difficult and approximate estimate of the residual neutralisation. Figure 6 shows the clearing system performance with regard to the electron beam emittance.

![Figure 6: EPA electron emittances at 530 MeV with clearing ON/OFF](image)

- The other effects of the clearing electrodes are: -
  - a lifetime similar to $e^+$ with clearing ON: $\lambda/2$ of the electron beam.
  - $\gamma$ and $\beta$ of the electron beam.
  - clearer on/off response on the adverse effects of ions on the beam (emittance blow up, transverse modes, beam stability, maximum intensity achievable).

7 Conclusions

The EPA vacuum and ion clearing systems have performed as expected during the first 2 years of running in at 500 MeV. The stainless steel vacuum system, fully vacuum fired, has shown a particularly low dynamic outgassing under synchrotron radiation exposure. Additional Argon glow discharge cleaning prior to installation has proved to be an interesting asset. More than adequate lifetimes for both electrons and positrons, fully compatible with single scattering on the CO molecules of the residual gas, have been obtained from the start. The ion clearing system based on new "invisible" clearing electrodes has proven to be essential to get comparable performance with $e^+$ as with $e^-$. With clearing, the maximum intensity stored more than doubles. However, there is still evidence of a small remnant neutralisation, revealed by transverse coherent ion-beam instabilities.

8 References