IONS AND NEUTRALIZATION

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ABSTRACT

After a short presentation of intensity limitations examples due to trapped ions, the processes of ionization and neutralization build up in particle accelerators and storage rings are briefly reviewed. The tolerable limits in neutralization are then assessed at the light of current theories of incoherent and coherent effects driven by ions. Finally the usual antidotes such as clearing electrodes, missing bunch schemes and beam shaking are presented.

1. INTRODUCTION

Charged particles created by ionization of the residual gas (ions, electrons) or dust (charged matter) by the circulating particles may be trapped in the beam's space charge potential, where they can cause beam loss or simply emittance blow up. Small electron storage rings (bunched) and antiproton accumulators (coasting) are extremely sensitive to this phenomenon (neutralization by ions). Proton storage rings with coasting beams (neutralization by electrons) such as the Bevatron and the ISR are also affected, but to a lesser extent. Large machines with bunched beams such as proton-antiproton (SPS-Tevatron) or electron-positron colliders (LEP) are not subject to ion trapping, as ions are either naturally unstable or have enough time to escape to the vacuum chamber wall in between bunch passages. Ions interact with the beam particles mainly via the Coulomb force: individually they add up to the residual gas density, thus enhancing single particle loss through Bremsstrahlung and single Coulomb scattering, and emittance blow up through multiple scattering at small angles. Macroscopically, due to their highly non-uniform longitudinal and transverse density, their collective space charge may represent non-linear optical defects which add to those of the machine magnet structure, thus enhancing the individual particle's incoherent motion (ion induced non-linear resonances), causing beam loss and emittance blow up. Last but not least, transverse collective coherent motion between the ion stream (or neutralization pockets) and the beam may exist, leading to emittance blow up and eventually beam loss.
Figures 1 and 2 below illustrate ion-induced intensity limiting phenomena, as experienced in the CERN EPA (Electron Positron Accumulator - 600 MeV) and AA (Antiproton Accumulator - 3.5 GeV/c) machines.

Figure 1: Beam lifetime $\tau$ in EPA as a function of beam current, with and without ion trapping [1]

Figure 2: Left, Emittance blow up in the CERN AA [4] caused by ion induced transverse coherent quadrupole instabilities. Right, the signal observed with a quadrupolar pickup electrode at the frequency of the unstable mode.
2. **ION PRODUCTION AND CONDITIONS OF TRAPPING**

Trapping occurs when electrons or positive ions resulting from a Coulomb collision between a beam particle and a residual gas molecule do not have enough kinetic energy to escape the beam space charge potential.

Ionisation of a gas atom is the result of an energy transfer $\Delta E$ (b) larger than the binding energy (or ionisation potential) of one of its orbital electrons in an elastic collision event with a beam particle [3]:

$$\Delta E (b) = \frac{(Ze)^2}{8 \pi^2 e_o^2 m c^2 \beta^2 b^2} > E_i$$  \hspace{1cm} (1)

where $e$ is the elementary charge, $Z$ and $z$ are the charge numbers of the incident and of the target particles, respectively, $c \beta$ is the velocity of the incident particle, $b$ the impact parameter (the minimum distance of the two particles during the collision) and $E_i$ the ionisation energy $\equiv z 13.5$ (eV) [5]. The mass of the target particle $m$ is $\sim 2 m_p$. $A$ for an atom of mass number $A$, $m_e$ for an electron ($m_p$ is the proton mass).

The above expression, only approximately valid for the useful range of impact parameters defined by the radii of the atom and its nucleus, can be used to show that the transferred energy to an electron and its nucleus is in the ratio:

$$\frac{2 m_p}{z m_e} = \frac{3672}{z} >> 1$$  \hspace{1cm} (2)

thus establishing the facts that beam energy loss is mainly on the electrons of the gas atoms, and that positive ions are essentially created at rest, i.e. with no or negligible kinetic energy resulting from the ionizing collision [3].

The rate at which one individual particle in the beam ionizes an atom is given by:

$$R_p = c \beta \Sigma n_j \sigma_j$$  \hspace{1cm} (3)

where $n_j$ and $\sigma_j$ are respectively the densities and ionization cross sections of molecules of gas species $j$. The cross sections depend on the molecule and on the beam relativistic speed by the Bethe formula [6]:

$$\sigma_j = 4 \pi \left(\frac{\hbar}{mc}\right)^2 (M^2 x_1 + C \beta^2)$$  \hspace{1cm} (4)

where $x_1 = \beta^2 \ln (\gamma^2 - 1)$ and $M^2$ and $C$ are characteristics of the molecules and $\hbar$ is Planck's constant. As a typical example, the values for EPA are shown in Table 1.
Distant collisions with large impact parameters — much more probable than close ones leading to ionisation — are important since they feed energy to the ions. In some circumstances (neutralization pockets) this may be a natural clearing mechanism, i.e. when the trapped species receive enough energy to escape the beam potential \( U \). This natural clearing rate can be calculated from the transferred energy \([3]\):

\[
R_c = \frac{2\pi m_e c^3 r_e^2 N_p}{eU} \log_n (3.10^4 z^{-2\beta})
\]

(5)

with \( m_e \) and \( r_e \) being \( m_e \), \( r_e \) if the trapped species is an electron, \( m_p \), \( r_p \) for a proton and \( 2m_p \), \( r_p \) for an ion of charge number \( z \). However the process is slow compared to typical ionization rates and Table 1 gives clearing rates for the EPA machine.

**Table 1**

EPA ionization cross sections and clearing rates (600 MeV, electrons with \( \gamma = 1200 \), \( P = 10^{-9} \) mbar)

<table>
<thead>
<tr>
<th>Gas</th>
<th>( \sigma_i (m^2) )</th>
<th>( R_p ) (s(^{-1}))</th>
<th>Ionisation time (s)</th>
<th>( R_c ) (s(^{-1}))</th>
<th>Clearing time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{H}_2 ) (( \sim 50% ))</td>
<td>( 0.4 \times 10^{-22} )</td>
<td>0.4</td>
<td>2.5</td>
<td>( 6.10^{-3} )</td>
<td>166</td>
</tr>
<tr>
<td>( \text{CO} ) (( \sim 50% ))</td>
<td>( 1.5 \times 10^{-22} )</td>
<td>1.5</td>
<td>0.7</td>
<td>0.04</td>
<td>25</td>
</tr>
</tbody>
</table>

The machine average neutralization is usually defined as

\[
\eta = \frac{N_i}{N_p} = \frac{R_p}{R_c} \leq 1
\]

(6)

where \( N_i \) and \( N_p \) are respectively the total number of ions and beam particles. A local value of the neutralization can be defined as

\[
\hat{\eta} = \frac{n_i}{n_p}
\]

where \( n \) relates to each species' density. An upper limit for \( \hat{\eta} \) is obviously 1 since larger values would reverse the beam-plus-ion space-charge potential, thus repelling ions to the wall.

Only in places where an external magnetic field confines excess ions (i.e. if no clearing), which is possible in quadrupoles [3] for instance, could \( \hat{\eta} \) be perhaps larger than one.

In the vast majority of cases (electron storage rings with typical pressures of \( 10^{-9} \) mbar and ionisation times of a second or less), ionization is the dominant effect in the absence of any clearing mechanism. Due to successive ionizations of already trapped ions, the neutralization builds up exponentially in time and reaches its maximum value in less than the primary ionization time. In
the limit of full neutralization, two mechanisms contribute to light-ion filling of the beam:

1) multiple ionization which can be shown to limit an ion species to a density equal to that of the residual gas one [3]; 2) heating by the beam, more pronounced for high-z species, becoming more and more efficient as the beam potential smears out when neutralization builds up [6].

If ion clearing is applied via electrodes, the maximum ion lifetimes are of the order of a ms or less, such that single-charge ions predominate [H₂⁺, CO⁺, CO₂⁺...]. This can be globally confirmed by measuring clearing currents on electrodes [7]. Figure 3 shows such a measurement for the AA. The total ion current is compatible with primary ionization events, using calculated cross sections (Eq. 4) and measured gas composition and pressure.

![Graph showing total ion current vs beam intensity](image)

Figure 3: Sum of ion current drawn on CERN AA clearing electrodes with N₀ = 6 x 10¹¹, and 90% H₂, 10% CO. The pressure is ≈ 3.10⁻¹¹ mbar.

3. CONDITIONS OF TRAPPING

3.1 Beam potential and ion pockets

The main trapping mechanism is the beam potential, since the ions at birth seldom have kinetic energies above thermal ones (i.e. < 1 eV), and this is usually not sufficient to overcome the potential energy given by the beam potential at the birth location for a singly charged ion [2]:

$$ U = \frac{\lambda}{2\pi \varepsilon_0} \begin{cases} \frac{r^2}{2a^2} - \frac{1}{2} + \log_n \left( \frac{r}{a} \right) & r \leq a \\ \log_n \left( \frac{r}{r_c} \right) & r \geq a \end{cases} \quad (7) $$

this expression being valid for a round uniform beam of radius a, line charge density λ, into a round vacuum chamber of radius r_c.
The log dependence of U on the ratio of chamber to beam radii shows that U is modulated along the machine azimuth. Any chamber enlargement (bellows, flanges) represents a potential well into which ions are trapped (they cannot move longitudinally: this is an "ion pocket"). In addition to a transverse oscillation of the ion in the potential well, there is an azimuthal ion drift resulting from the longitudinal beam potential gradient which usually dominates the thermal motion and the beam induced electro-magnetic force [3]. For low values of the neutralization, typical longitudinal electric fields due to the variation of lattice functions alone are of the order of a fraction to a few V/m, resulting in ion azimuthal velocities of several km/s in field free regions.

3.2 External magnetic fields

The main effect of an external magnetic field is to induce a cycloidal motion in the azimuthal direction, perpendicular to the field lines, resulting in drifts along the beam with velocities [2]:

\[ v_B = \frac{E_x}{B} \]  \hspace{1cm} (8)

\[ v_B = W_{\text{kin}} \frac{1}{g e B^2} \frac{\delta B}{\delta x} \]  \hspace{1cm} (9)

where B is the magnetic field, E the beam space charge, x the transverse horizontal coordinate, \( W_{\text{kin}} \) the ion kinetic energy in the plane perpendicular to B, and g e the electric charge of the ion.

These drift velocities, of the order of several 100 m/s to km/s at the edge of the beam, fall to zero or very low values for ions born at the center of the beam (the drift along the beam is in opposite directions on either side of its axis). For this reason, the possibility of high ion neutralization levels in magnets exists, and it is important to place clearing electrodes in these locations. In uniform magnetic fields, the motion parallel to the field of the center of gyration of the cyclotron motion is not affected by the field.

Magnetic mirror effects occur for low energetic ions drifting from field-free regions towards magnet fringe fields (for some conditions of creation). The longitudinal gradient of the field may reverse the ion motion thus creating a barrier [8]; for this reason sections between magnets must incorporate clearing electrodes. Similar effects are suspected for electrons repelled by the beam potential in quadrupoles; the gradient along the field lines may provoke a containment effect, resulting in an enhanced local ionization rate (electrons from ionization are much more energetic than ions and may ionize the gas) [3].

Without clearing, coasting beam machines with negative space charge such as antiproton
accumulators can reach very high neutralization levels, close to one [9]. DC proton machines trapping electrons, such as the ISR [10], reached neutralization values of a few percent only, most electrons at birth receiving enough momentum to escape the beam potential.

3.3 Ion stability in bunched-beam machines

As we have seen the main force from the beam on an ion is radially focusing; it results from the space charge and leads to the equation of motion:

\[ \ddot{x} + k_x x = 0 \]  

(10)

where \( k = \frac{2e \delta E}{m \delta x'} \) with \( E \) the beam electric field. For a continuous (DC) beam, \( E \) does not depend on time and the resulting motion is a transverse harmonic oscillation (to first order) of frequency \( \omega \) (bounce frequency) and constant amplitude.

When the beam is bunched, the \( k \) term in (10) becomes a periodic function of time, yielding the possibility of parametric resonances and thus of open transverse motion for the ions (i.e. loss). It is for this reason that bunched beams reach lower neutralization levels than coasting ones, at least for some conditions of size, emittances, number of bunches and intensity thresholds, contained into a single criterium: the critical mass to charge ratio of the ion.

For uniformly spaced equal bunches around a machine such that an ion receives a succession of instantaneous kicks, similarly to particles travelling through a series of thin focusing lenses, Eq. (10) becomes a Hill equation and yields the following condition of stability for a singly-charged ion of mass-to-charge ratio \( A_i / g \) (\( g = 1 \)) [11]:

\[ A_i > A_c = \frac{N_p}{2 \pi^2} \frac{\pi R}{\sigma_x^2 \left( 1 + \frac{\sigma_x}{\sigma_y} \right)} \]  

(11)

with \( R \) the radius of the machine, \( N_p \) the total number of particles, \( n \) the number of bunches, \( \sigma_x \) and \( \sigma_y \) respectively the rms horizontal and vertical beam sizes.

All ions with a mass-to-charge ratio less than the critical mass are unstable and cannot be trapped. Given that all possible ions lie usually in a mass-to-charge range of 1 to 44, then if the critical mass is less than 1, neutralization can reach high values, close to 1, similarly to coasting beams. This is the case of many small electron storage rings with large number of bunches.

Other machines which do not fulfill this condition, i.e. with critical masses higher than 1 or 2, or which have non-uniform bunch distributions, may also be plagued by some neutralization.
However, in principle, their ion density should be limited to the molecular density, yielding a neutralization of a fraction to a few percent, depending on the vacuum performance [3–12]. Finally, in the case of large colliders, for which the theory of ion trapping has been also well developed [11], their size prevent them from having neutralization problems.

4. TOLERABLE LIMITS IN NEUTRALIZATION

4.1 Incoherent effects

4.1.1 Incoherent tune shifts

In analogy to the radial (centripetal) force exerted by the beam space charge on an ion, a beam particle senses the focusing force from the ion-cloud space charge. Integration of this force around the ring yields a change of particle tunes $\Delta Q_{x,y}$. Assuming a perfect superposition of the ion and beam particle transverse distributions (elliptic bi-gaussian) one finds for a particle in the beam center [13]:

$$\Delta Q_{x,y} = \frac{r_p \beta_{x,y} N_p}{2\pi \beta \gamma} \sigma_{y,x}^2 \left( 1 + \frac{\sigma_{x,y}^2}{\sigma_{y,x}^2} \right)$$

(12)

with the classical proton ($r_p$) or electron ($r_e$) radius for respectively a proton (or antiproton) and an electron beam, $\beta_{x,y}$ the average $\beta$ functions in the two planes $x$ or $y$.

Expression (12) gives the maximum tune shift. Beam particles at the edge of the transverse momentum distribution or with large betatron amplitudes experience less focusing from the ion space charge (zero at the limit), such that $\Delta Q_{x,y}$ also represent approximately the ion-induced tune spreads. This is illustrated in figure 4, taken from the AA.

![Figure 4](image)

Figure 4: Left: antiproton transverse tunes as function of their momentum, with full (no clearing) and little (clearing) neutralization. Right: particle emittances (independant of neutralization during the measurement).
The ion-induced incoherent tune shift (and spread) can take very large values for small machines ($\gamma$ small). As examples, for EPA ($E = 600$ MeV, $\gamma = 1200$, $N_p = 6.10^{11}$ electrons) [14]:

$$\Delta Q_{\text{ions}} = 0.15 \eta \text{ (i.e. - 0.15 without clearing)}$$

and for the AA ($p = 3.5$ GeV/c, $N_p = 10^{12}$ antiprotons):

$$\Delta Q_{\text{ions}} = 0.01 \eta \text{ (i.e. - 0.01 with no clearing)}.$$

On some small, low energy electron storage rings, the ion space-charge tune shift could even reach half integer values.

It is interesting to compare the neutralization (focusing) and direct beam space charge (defocusing) effects. The maximum total tune shifts produced by the neutralization and the beam space charge are given by:

$$\Delta Q_{x,y} = \frac{r_{\beta}}{2 \pi \beta \gamma B} \frac{N_p}{\sigma_y^{2,x}} \left[ \frac{\hat{\eta} - \frac{1}{\gamma^2}}{1 + \frac{\sigma_y^{x,y}}{\sigma_y^{x,x}}} \right]$$  \hspace{1cm} (13)

with $B$ the bunching factor ($B = n_{lB}/2\pi R << 1$ for bunched beams) and $\hat{\eta} = B\eta$.

On small machines (which trap ions most easily), ions may dominate the beam space-charge tune shift. For the same conditions as above:

$$\text{CERN AA} : \Delta Q_{\text{ions}} \leq 10 \Delta Q_{\text{sp. charge}}$$

$$\text{CERN EPA} : \Delta Q_{\text{ions}} \leq 10^4 \Delta Q_{\text{sp. charge}}$$

The incoherent space-charge tune shift expression (13) provides a means to measure the average neutralization in a ring [12]. This supposes the possibility of clearing the beam of its ions (clearing electrodes, beam shaking, asymmetric bunch filling) so that from measurements of the tunes $Q$, with and without ions, $\eta$ can be obtained from (13) (note that the sign of the shift already tell us if the beam is space-charge or ion dominated). $\Delta Q$ is usually extracted from frequency spectral analysis of a transverse betatron side-band (the difference signal from a pair of electrodes around a beam mode frequency ($n \pm Q)f_{\text{rev}}$. Obtaining the maximum frequency shift experienced by a particle by comparison of two transverse spectra is only approximate (the measurement shown on figure 4 requires unfolding several spectra [15]). If one supposes identical initial bi-gaussian transverse distributions for the beam particles and the ions, the maximum frequency shift $\Delta Q$ can be obtained by multiplying the shift of the peaks of the distributions by approximately 2.5 [16].

4.1.2 Resonances

Tune shifts due to ions cause particles to cross resonance lines in the tune diagram:
\[ n Q_x + m Q_y = \text{integer} \]
\[ n, m = 0, \pm 1, \pm 2 \ldots \]
resulting in transverse amplitude growth (emittance blow up) and eventually loss.

Very similarly to the excitation of non-linear resonances by the beam-beam interaction in colliding beam machines, the electrostatic field of ion clouds in neutralization pockets causes non-linear detuning, and its uneven distribution may excite very high order resonances (up to 15th order in the AA, [9]). This effect, still present at low neutralization levels of a fraction of a percent, is very detrimental for antiproton accumulators which have low transverse emittance cooling rates (compared to electron storage rings). As the beams are unbunched, the neutralization can only be coped with by reducing the ion density through shaking of the beam (see section 5.3). Figure 5 shows a measurement of transverse heating rates due to the excitation of high-order resonances by ion pockets in the AA. [9].

![Graph showing net resonance-induced emittance heating rates versus tune in the AA, due to residual neutralization pockets.](image)

Figure 5: Net resonance-induced emittance heating rates versus tune in the AA, due to residual neutralization pockets.

These heating rates occur at a neutralization level of a few percent, if the betatron frequencies of the particles concerned cross the resonance continuously, gaining amplitude at each crossing. This is explained in this case by a tune modulation caused by the ripple of the quadrupole power supplies [17] (the equivalent of the synchrotron tune modulation for the beam-beam effect in colliders).
In electron storage rings, the emission of synchrotron radiation by the circulating particles results in high damping rates for their transverse motion, so that it is unlikely (but not proven) that such high-order resonances can be harmful, since their strength decreases as their order increases. However due to the strong coupling introduced by the ion electrostatic force (which depends on both transverse coordinates x and y), and due to the fact that no other natural vertically heating mechanism exists in these machines (scattering on gas being negligible), even a small neutralization level may quickly manifest itself by an increased vertical beam size. Experience on modern machines shows that ion-induced tune shifts of a few $10^{-3}$ caused by neutralization levels of a few percent or less, already present annoying emittance effects.

One of these, common to some synchrotron radiation sources, is a pulsation of the vertical beam size. This occurs when the emittance growth rate due to an ion-induced resonance is larger, and the neutralization rate smaller, than the natural damping rate. As the beam inflates ions are chased away by the resonance, the beam then shrinks, neutralization builds up again and the process repeats itself in a sort of relaxation mechanism [18].

To summarise, experience on incoherent effects so far shows that tolerable neutralization levels should limit the maximum ion-induced tune shifts to $\sim 10^{-2}$ in electron storage rings with radiation damping, and to less than $10^{-3}$ in antiproton storage rings. The corresponding tolerable average neutralization may range from a fraction to a few percent.

4.2 Coherent instabilities

In addition to single-particle phenomena, transverse coherent instabilities, where collective oscillations of the beam center or the beam shape grow exponentially due to the interaction with the trapped species, have been identified on several machines (electron-proton in the CERN ISR and LBL Bevatron [10], ion-antiproton in the CERN and FNAL Antiproton Accumulators [9-20], ion-electron in the CERN PS [21]). These instabilities, which cause fast emittance blow up of the beams and eventually loss of particles, can occur at lower neutralization levels than single-particle phenomena. Ion-driven dipole and quadrupole coherent instabilities have represented severe intensity limiting mechanisms in the CERN AA, where they have been studied in detail [19].

In order to guess the tolerable neutralization with respect to these instabilities, we shall glance at the classical two-beam instability theory developed by Koshkarev and Zenkevich [22] and Lasslett, Sessler and Möhl [23], restricted to coasting beams.

In collective motion, the beam center or shape moves in a travelling wave pattern described by:
Figure 6: Beam wave patterns for coherent modes. a) dipole mode - b) quadrupolar mode.

With $\omega_r$ the revolution frequency, $R$ the ring radius, $s$ the azimuth along the beam. The mode number $n = 1, 2, 3...$ is equal to the number of nodes around the ring.

The mode frequency, as seen by a pick-up electrode at a fixed azimuth is

$$\omega_n = \frac{l}{n} (n + lQ) \omega_r$$

where $l = 1$ for a dipole mode, 2 for a quadrupole mode, etc...

Due to the spread in betatron frequencies, the signal seen by the pick-up (Schottky band) has a certain width in frequency as sketched below:

Figure 7: Pick-up signal around a transverse beam mode frequency for a coasting beam (Schottky band). $\omega_r, \delta Q$ is the maximum mode frequency shift induced by the ion force on the beam.
Transverse coherent ion-beam coupled oscillations leading to instability are possible when the ion-bounce frequency lies close to the natural beam mode, in a band $\omega_0, \delta Q$. $\delta Q$ reflects the force applied by ions on the beam and is obtained by solving the dispersion relation of the equation of motion without frequency spreads.

With the approximations of linear forces (i.e. uniform particle distributions superposed), neglecting image forces and averaging the lattice contributions, these equations are for a dipole mode \[19\] :

\[
\begin{align*}
\text{particle} & \quad \frac{1}{\omega_0^2} \ddot{y} + Q_{o}^2 y - Q_{sc}^2 (y - \bar{y}) + Q_{c}^2 (y - \bar{y}) = 0 \\
\text{ion} & \quad \frac{1}{\omega_0^2} \ddot{y_i} + Q_{sc}^2 (y_i - \bar{y_i}) + Q_{c}^2 (y_i - \bar{y_i}) = 0
\end{align*}
\] (14)

where the bar on the transverse coordinate represents the motion of the beam center, $Q_o$ the particle unperturbed tune (only lattice dependent), and the other $Q$-$q$ being the various space charge forces.

$Q_{sc}$ the particle-particle space charge :

\[
Q_{sc}^2 = \frac{2 N_p r_o R}{2 \pi \sigma_x (\sigma_x + \sigma_y) \beta^2 \gamma^3}
\] (15)

$Q_c$ the ion space charge on particle :

\[
Q_{c}^2 = \frac{2 \eta N_p r_o R}{2 \pi \sigma_x (\sigma_x + \sigma_y) \beta^2 \gamma}
\] (16)

(with $r_o$ being $r_e$ or $r_p$ for an electron or hadron beam),

$q_c$ the beam space charge on the ion of charge $g$ for and atomic mass $A$ ($g = A = 1$ for a trapped electron) :

\[
q_{c}^2 = \frac{2 N_p r_{p,e} R g}{2 \pi \sigma_x (\sigma_x + \sigma_y) \beta^2 A}
\] (17)

$q_{sc}$ the ion-ion space charge : $q_{sc}^2 = \eta z q_{c}^2$ and putting $Q_{o}^2 = Q_{o}^2 + Q_{c}^2 - Q_{sc}^2$; $q_{c}^2 = q_{c}^2 - q_{sc}^2$.

Starting from Eq. (14), four similar linear equations can be derived for the beam transverse shape first-order variations in a quadrupole mode (variables $\xi$ and $\xi$ of figure 6).

In the approximation of round beams ($\sigma_x = \sigma_y$), it is found that the risk of transverse instabilities exists in a band given by :

\[
\delta Q = \frac{q_{c} Q_{c}}{\sqrt{q_{c} Q_{o}}}
\] (18)
where \( p = 1 \) for a dipole mode, \( p = 1/2, 1/4 \) respectively for a symmetric \((\zeta = \xi)\) or antisymmetric \((\zeta = -\xi)\) quadrupole mode. The width of this band, reflecting the risk of instability, is proportional to the strength of the force on the beam exerted by the ions \( Q_o \), i.e. to the square root of the neutralization coefficient (Eq. (16)). It is smaller for quadrupole than for dipole modes.

For realistic frequency distributions the spreads in mode and ion frequencies \( \Delta n \) and \( \Delta i \), i.e. the spreads of \( \omega /\omega_q \) and \( q \) respectively, introduce Landau damping in this band when three conditions are simultaneously satisfied:

\[
\Delta n > p \left| \frac{Q^2_{se}}{Q} \right| ; \Delta i > p \left| \frac{q^2_{se}}{q} \right| ; \Delta n \Delta i > p^2 \left| \frac{Q^2 q^2}{qQ} \right|
\]  

(19)

with \( p=1, p = 1/2 \) or \( p = 1/4 \) as defined under Eq. (18).

Thus, the required spreads are smaller by \( p \) and the threshold neutralisation \((\eta \sim Q_o)\) is higher by \( p^{-2} \) for quadrupole instabilities. In the AA, quadrupole instabilities appeared after dipole ones had been damped by transverse feedback, at 2 to 3 times higher beam intensities, causing large beam amplitudes and loss of particles. The application of the theory outlined above fitted observations when assuming a single ion pocket representing an average neutralization of \( 10^{-3} \) or less [19]. Expressions for these instability growth rates and maximum beam amplitudes can be derived. In general and especially for the dipole mode, the amplitudes of the trapped species are much larger than those of the main beam. Therefore, for beam transverse excursions of a fraction of a millimeter, the trapped particles are lost to the walls of the vacuum chamber, or simply detuned, causing a slight emittance blow up of the main beam. Ions are cleared by these instabilities; the continuous creation of new ions from the residual gas may either feed a constant amplitude wave pattern of the beam, or provoke a relaxation mechanism similar to the incoherent effects [24].

Much work is still required to understand quantitatively the tolerable limits of neutralization to avoid coherent instabilities. Many necessary ingredients such as the types and the lifetimes of trapped ions and the location of neutralization pockets around a ring are usually unknown; if they were known, much refinement would have to be added to the theory to describe the experimental observations.

However, from the experience of existing machines, it is certain that to avoid coherent instabilities neutralization levels have to be extremely low, certainly well below 1% on the average. This level is difficult to achieve with the actual clearing means for small electron or antiproton machines [25].

5. CURES

At present there are four methods to fight against ion build up, maintenance of the best possible
vacuum, uneven bunch filling, clearing electrodes and beam shaking.

5.1 Vacuum conditions

Good vacuum acts through the ion production rate \( R_p \) (thus reducing \( \eta = R_p/R_e \)) and ion type. UHV conditions, defined as \( p < 10^{-9} \) mbar, imply mainly hydrogen as the residual gas. This has small ionization cross sections, and low z and mass (i.e. eventually untrappable or easy to remove because of high velocities). It is therefore essential that neutralization-prone machines have an extremely good vacuum. This means an efficient pumping system, together with a careful choice, preparation and in situ baking of all components in contact with the machine vacuum.

5.2 Uneven bunch filling

Many small electron storage rings partly solve the problem of ion trapping by introducing one or several gaps in the bunch train by not filling certain buckets at injection. This has the effect of introducing large stop-bands in the ion transverse frequency spectrum, or, in other words, bands of unstable mass-to-charge ratios in the ion mass spectrum [26]. Because an initially stable trapped ion can be further ionized, its mass-to-charge ratio decreases, and thus it has a chance to fall in an unstable band and to be cleared away. The neutralization is therefore reduced, but at the expense of the total beam intensity of the machine.

5.3 Clearing electrodes

Another common way to extract ions from the beam consists in installing a negatively polarized plate close to the beam, providing a transverse electric field which extracts beam-channelled ions. The potential \( U_c \) applied to the electrode must be such that it exceeds the maximum beam space-charge field in order to capture all the passing ions [3]:

\[
\frac{U_c}{d} > E_{\text{max}} \sim \frac{I}{4\pi \varepsilon_0 \beta c a}
\]  

for a round uniform beam of current \( I \) and radius \( a \), \( d \) being the distance between the plate and the opposite vacuum chamber wall.

Because ions may have large velocities (transverse if born on the edge of the beam, longitudinal if born at the center) and electrodes are necessarily limited in size, the voltage to be applied for optimum clearing may represent several times this value [7].

A large number of electrodes is required to achieve a low neutralization. Strategic locations are straight sections close to fringe fields, dipole magnets, quadrupoles and pockets created by vacuum chamber cross-sectional changes: all places where ions are likely to accumulate or have low drift velocities. However there are also arguments against a large number of electrodes; they may
represent a sizeable contribution to the machine transverse and longitudinal beam coupling impedance unless great care is taken in their design. Figure 8 shows the distribution of electrodes, presenting negligible longitudinal coupling impedance, in the EPA [1]. The button electrodes are made of an alumina body, coated with a few 10 μm thick resistive layer ($R_{\text{square}} \sim 30$ kΩ), thus making it transparent to electromagnetic waves ($R_{\text{square}} \gg 377\Omega$).

![Diagram of EPA and electrode distribution](image_url)

Figure 8: Distribution of clearing electrodes around EPA and cross section of one electrode

5.4 Beam shaking

In practice it is extremely difficult to design a fully efficient clearing system for ions. Beam shaking has been successfully applied to reduce the ion concentration - and thus their action on the beam - in uncleared ion pockets [27]. It consists in using the beam, transversally driven in coherent motion by a pair of kicker electrodes fed by an RF voltage, to excite the trapped ions to large amplitudes. Experimentally [20], beam shaking has been shown to reduce neutralization effects and to have the following characteristics:

- it works best when applied vertically and when the frequency is just above an $n+Q$ side band, and just below an $n-Q$ band
- it is efficient even with a low RF field (10 V/m) when the shaking frequency is close to a betatron side band (resonant mode shaking [4]) of the main beam
- the shaking frequencies have to be carefully chosen to be close to the ion bounce frequencies ($H_2^+$, $CO^+$) in the potential of the circulating beam
- the average neutralization has to be low (i.e. there must be other clearing mechanisms).

To understand some of these features, and in particular how ions can respond to a single harmonic excitation of the beam, the special features of resonance in non-linear oscillations (the ion in the non-linear beam space charge) will be briefly described [25].
The motion of the normalized vertical displacement $v$ of an ion from a beam center oscillating harmonically at the shaking frequency $\omega$:

$$y_c = y_{\infty} \sin (\omega t)$$

defined as

$$v = \frac{v - y_c}{2 \sigma_y}$$

can be written as

$$\ddot{v} + \omega_{iy}^2 v = f(v) + \omega^2 H \sin (\omega t)$$  \hspace{1cm} (21)

where $H = y_{\infty}/2 \sigma_y$ is the amplitude of the external forcing, and

$$\omega_{iy} = \left( \frac{g I}{4 \pi \varepsilon_0 \beta c m \sigma_y (\sigma_x + \sigma_y)} \right)^{1/2}$$  \hspace{1cm} (22)

is the vertical ion bounce frequency. $f(v)$ retains the non-linear terms resulting from a series expansion of the electric field ($f(v) \sim o$ for small $v$). The small amplitude solutions of equation (21) at equilibrium, studied by a perturbative method, for shaking frequencies $\omega$ close to $\omega_i$ satisfy [25]:

$$\frac{\omega}{\omega_i} = \left( \frac{a G (a^2)}{a + H} \right)^{1/2}$$  \hspace{1cm} (23)

where $G (a^2)$ is a non-linear function of the system. Figure 9 shows the well-known curves giving the equilibrium amplitudes $a$ as a function of $\omega/\omega_i$.

Figure 9: Equilibrium ion amplitudes as a function of the shaking frequency $\omega$. The dotted line corresponds to unstable solutions. For $\omega/\omega_i$ above the transition point $T$, ions can have either small (lower curve) or large amplitudes, depending on initial conditions.

For highly neutralized beams (no clearing), ions have a broad spectrum of plasma frequencies, dependent on the neutralization by other species. In addition, due to the small beam-plus-ion space-
charge potential, their drift velocities are very low such that their frequencies do not change rapidly. In this case shaking at one fixed frequency only affects a small fraction of them and is not efficient. This probably explains why shaking does not work when the clearing electrodes are turned off in AA and EPA.

When the clearing electrodes are on, only a low neutralization remains, concentrated in a few portions of a machine, thus reducing the spectrum of ion frequencies. In addition ions move faster along the beam due to higher potential gradients, and their frequencies scan this spectrum. Ions for which frequencies decrease follow the path A of figure 9 and provided this scanning of the resonance is not too fast, they "lock-on" to it and keep large amplitudes, thus reducing their density in the center of the beam. Ions following path B, that is those with increasing plasma frequencies, experience only a small jump at the crossing of the resonance and are not excited to large amplitude. This hysteresis phenomenon, jump bifurcation or so-called lock-on effect characteristic of non-linear resonances [27] explains the efficiency of shaking, and leads to an asymmetry in the ion behaviour. In particular, in conjunction with clearing current measurements, beam shaking has permitted the identification of ion neutralization pockets in the bending magnets of the CERN AA [7].

Figure 10 illustrates the effect of shaking the coasting antiproton beam vertically at 400 kHz (i.e. just below the fractional vertical tune frequency corresponding to the \(o + q\) band, where \(q\) is the non-integer part of the tune) in the FNAL Antiproton Accumulator. The decrease in beam emittances and the increased stacking rate are a consequence of reduced ion densities [28].

Figure 10: Reduced beam emittance and increased stacking rate in the FNAL Antiproton Accumulator with beam shaking
6. CONCLUSION

Neutralization by ions from the residual gas in modern machines such as antiproton accumulators, synchrotron light sources and future B factories is still a challenge. The physics of neutralization and the ion dynamics are only partly understood, as are also the effects on the beam. Despite some progress made in minimizing their coupling with the beam, clearing electrodes are probably not sufficient to reduce the neutralization to acceptable levels in high intensity machines. Beam shaking has been shown to be an efficient additional antidote on some machines, but much progress has to be made both in its understanding and application. Ideas such as frequency modulated shaking, multi-frequency and cyclotron shaking have been proposed [25], which still need to be tested experimentally. All aim at improving further the efficiency of the process, to reduce the neutralization to acceptable levels even in the most difficult cases.
REFERENCES


