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Ion clearing in an ERL

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Abstract

The rest-gas in the beam-pipe of a particle accelerator is readily ionized by effects like collisions, synchrotron radiation and field emission. Positive ions are attracted to electron beams and create a nonlinear potential in the vicinity of the beam which can lead to beam halo, particle loss, optical errors or transverse and longitudinal instabilities. In an energy recovery linac (ERL) where beam-loss has to be minimal, and where beam positions and emittances have to be very stable in time, these ion effects have to be avoided. Here we investigate three measures of avoiding ion accumulation: (a) A long gap between linac bunch trains that allows ions to drift out of the beam region, a measure regularly applied in linacs; (b) a short ion clearing gap in the beam that leads to a time varying beam potential and produces large excited oscillations of ions around the electron beam, a measure regularly applied in storage rings; (c) Clearing electrodes that create a sufficient voltage to draw ions out of the beam potential, a measure used for DC electron beams and for antiproton beams.

For the parameters of the X-ray ERL planned at Cornell University we show that method (a) cannot be applied, method (b) is technically cumbersome, and (c) should be most easily applicable.

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1. Introduction

Cornell is planning to build an X-ray facility based on an ERL extension of the storage ring CESR that is currently used for the Cornell High Energy Synchrotron Source (CHESS) [1,2]. Fig. 1 shows the CESR tunnel and the layout of the ERL extension. Electrons from a 10 MeV injector (1) would be accelerated to the right in a 2.5 GeV linac (2). A return loop (3) would send them into a second linac which is located in the same straight tunnel (4) and accelerates to 5 GeV. An arc (5) injects the electrons into the CESR ring (6) where they travel counterclockwise until another arc (7) injects them back into the first linac, where they are decelerated to 2.5 GeV. The return loop leads the electrons to the second linac section where deceleration back to 10 MeV leads to the beam dump (8) [3].

A return arc is also shown which connects the arcs (5) and (7) so that electrons can return to the linacs after acceleration without passing through CESR. This connection has been chosen so that the ERL could be built and commissioned while CESR is still used as a storage-ring light source. Other advantages of this upgrade plan are that all of the CESR tunnel is reused, which creates space for a large number of insertion devices. The straight tunnel houses two linacs, which reduces tunnel cost as well as the required length of cryogenic lines and cables. The tunnel is laid out longer than required for the two linacs, so that an extension of the facility by extra undulators or by an FEL is possible.

In the white-paper description [1] of Cornell's X-ray ERL the issue of positive ions close to the electron beam was discussed in the following way: It was calculated how long it takes until a significant optical error is created by the accumulation of ions in the electron beam's potential. It was then proposed to have an ion clearing gap after a bunch train that is no longer than this accumulation time. The length of the following ion clearing gap was determined by the time it takes ions to drift out of the beam potential and to hit the chamber wall. Below we have

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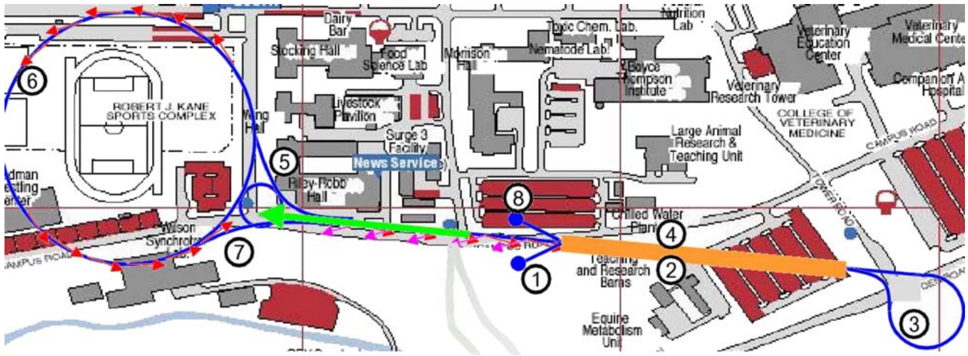

Fig. 1. An ERL in an extended CESR tunnel.

redone these calculations for parameters of an ERL extension to the CESR ring.

We also evaluate transient effects of the RF system at the start of each bunch train and at the start of each clearing gap. It turns out that these transient effects require the ion clearing gap to be very long.

In storage rings, ion clearing gaps have to be quite short, i.e. a fraction of the circumference of the ring. This does not give enough time for all ions to drift out of the beam region and the ion clearing mechanism therefore has to differ from that in linacs. In rings, a short ion clearing gap that has a fraction of the circumference gives the attractive beam potential a time structure so that the ions experience a time dependent force with many frequency components. Ions are therefore exited to large oscillations, and are thereby cleared out of the beam region. When this ion clearing approach is used, it has to be checked that no relevant ion species accumulate in the beam's potential.

Even though an ERL has only one, or a very limited number of loops, this strategy of cleaning ions with frequent but short clearing gaps can be used. It has the advantage that transient RF effects are avoided when the distance between clearing gaps is a integer fraction of the length of the ERL loop, so that the bunch-gap in the accelerating and in the decelerating beam coincide.

Transient RF effects will however remain in the injector linac, which at Cornell accelerates a beam current of 0.1 A to 10 MeV, and in the electron gun, where this current is accelerated in a 0.75 MV cathode–anode gap. It is shown below that in both instruments these effects are very destructive, and if no remedy is found the ions have to be cleared with static electric fields. These are created by electrodes which produce an electric force that pulls ions out of the electron beam potential. At the electrodes ions are neutralized and return into the gas phase. Often the buttons of beam position monitors have been put on an electric potential for that purpose. However, since one cannot have such electrodes along the complete beam-pipe, they have to be positioned at locations where ions accumulate due to longitudinal electric forces, and the time it takes ions to drift to these longitudinal positions has to be appropriately short.

Three working modes of the planned Cornell X-ray ERL are investigated:

(1) A high current mode with a current of $I = 100\,\mathrm{mA}$ where every RF bucket would be filled. The nominal emittance is $\varepsilon_{xn} = \varepsilon_{yn} = 1 \times 10^{-6}\,\mathrm{m}$, even though calculations have shown that the injector which is currently being built has the potential for significantly smaller emittances.
(2) A high brilliance mode with reduced current of $I = 10\,\mathrm{mA}$ and reduced emittances of $\varepsilon_{xn} = \varepsilon_{yn} = 0.1\times\ 10^{-6}\,\mathrm{m}$. All other parameters are equivalent to mode (1).
(3) A short bunch mode with bunch length of $\sigma_t = 100\,\mathrm{fs}$ while only every 1300th bucket is filled. The average current is $I = 1\,\mathrm{mA}$ so that the bunch charge is 13 times larger than in mode (1). The emittances are assumed to be $\varepsilon_{xn} = \varepsilon_{yn} = 5 \times 10^{-6}\,\mathrm{m}$. All other parameters are assumed to be equivalent to mode (1).

The RF frequency is $\nu_{\mathrm{RF}} = 1.3\,\mathrm{GHz}$. Other relevant parameters are the following: In the main section of the ERL, from the start of the main linac at an energy of $E_{\mathrm{low}} = 10\,\mathrm{MeV}$ to the return loop at $E_{\mathrm{high}} = 5\,\mathrm{GeV}$ and back through the decelerating linac, the average beta function will be assumed to be $\beta_{\mathrm{aver}} = 50\,\mathrm{m}$ and the minimal beta function will be assumed to be $\beta_{\mathrm{min}} = 1\,\mathrm{m}$. The bunch length is $\sigma_t = 2\,\mathrm{ps}$ and the gas pressure is assumed to be $p_{\mathrm{gas}} = 6 \times 10^{-10}\,\mathrm{Torr}$, which is the pressure that is achieved in CESR under good conditions.

2. Ion trapping

2.1. Trapping in bunched beams

Assuming the beam is infinitely long and has a Gaussian shape in the transverse direction, its Coulomb potential can be computed [4]. In linear approximation in x and y the transverse forces are given by

$$\vec{F} = \frac{e^2}{4\pi\varepsilon_0}\frac{\lambda}{\sigma_x+\sigma_y}\begin{pmatrix}\frac{x}{\sigma_x}\\ \frac{y}{\sigma_y}\end{pmatrix} \tag{1}$$

with λ being the number of electrons per length of the beam. In the rest of the paper, this formula will always be used when computing the force that an ion experiences in the electron beam.

The electron beam has n_e electrons per bunch where bunch centers are a distance ΔL apart. When the ion beam partially neutralizes the electron beam by a fraction θ, the average charge density is $en_e/\Delta L(\theta-1)$. The attracting force in the vertical plane during the bunch gap is

$$F_y = \frac{e^2}{4\pi\varepsilon_0}\frac{n_e\theta}{\Delta L}\frac{1}{\sigma_x+\sigma_y}\frac{y}{\sigma_y}. \tag{2}$$

During the electron bunch of length σ_s the average focusing force is

$$F_y = -\frac{e^2}{4\pi\varepsilon_0}\frac{n_e}{\sigma_s}\left(1-\theta\frac{\sigma_s}{\Delta L}\right)\frac{1}{\sigma_x+\sigma_y}\frac{y}{\sigma_y}. \tag{3}$$

With $\kappa=\sigma_s/\Delta L$, the vertical velocity $\dot{y}$ that an ion accumulates while a bunch of length σ_s passes is then approximately

$$\Delta\dot{y} \approx -A_{\text{ion}}^{-1}(1-\theta\kappa)\frac{n_e r_p c}{\sigma_x+\sigma_y}\frac{y}{\sigma_y} \tag{4}$$

and over a bunch gap $\Delta L_g = \Delta L - \sigma_s$ it is

$$\Delta\dot{y} \approx A_{\text{ion}}^{-1}\theta\frac{\Delta L_g}{\Delta L}\frac{n_e r_p c}{\sigma_x+\sigma_y}\frac{y}{\sigma_y} \tag{5}$$

with the classical proton radius $r_p = e^2/4\pi\varepsilon_0 m_p c^2$.

Using the linear focusing force that the ions experience while they are within the electron bunch, the vertical phase space point changes according to a quadrupole matrix, which in thin lens approximation leads to

$$\begin{pmatrix}y_1\\ \dot{y}_1\end{pmatrix} = \begin{pmatrix}1 & \frac{\sigma_s}{c}\\ -\alpha & 1\end{pmatrix}\begin{pmatrix}y_0\\ \dot{y}_0\end{pmatrix}. \tag{6}$$

During the gap between bunches the ions are defocused under their own Coulomb expulsion,

$$\begin{pmatrix}y_2\\ \dot{y}_2\end{pmatrix} = \begin{pmatrix}1 & \frac{\Delta L_g}{c}\\ \beta & 1\end{pmatrix}\begin{pmatrix}1 & \frac{\sigma_s}{c}\\ -\alpha & 1\end{pmatrix}\begin{pmatrix}y_0\\ \dot{y}_0\end{pmatrix}. \tag{7}$$

The focusing strengths α and β are defined by Eqs. (4) and (5). This motion is stable when the trace of the matrix has an absolute value between 2 and -2,

i.e. if $4 > \alpha\frac{\Delta L_g}{c} - \beta\frac{\sigma_s}{c} = A_{\text{ion}}^{-1}\frac{n_e r_p \Delta L_g}{(\sigma_x+\sigma_y)\sigma_y}\ (1-2\theta\kappa)$.

The condition for ion trapping in the vertical dimension in linear theory [8,5] is therefore

$$A_{\text{ion}} \geqslant \frac{n_e r_p}{4(\sigma_x+\sigma_y)\sigma_y}\Delta L_g \tag{8}$$

when either $\sigma_s \ll \Delta L$ or $\theta \ll 1$. For trapping in the horizontal dimension x and y have to be interchanged. The smaller of the two beam dimensions leads to the more stringent equation.

The smaller the beam size, the larger the attracting field of the electron current, and the larger the mass of the positive ion has to be in order to be trapped. Also, for a longer distance between bunches, ions have time to escape the attracting force of the bunches and ions have to be heavier to be trapped. In the operation modes (1) and (2) where $\Delta L = c/\nu_{RF} = 0.23\,\text{m}$, no ion can escape the beam potential and the electron beams appear to the ions as a charged string or ribbon. In the short pulse operation mode (3), the bunches are separated by 1 μs and only particles with $A > 28$ will be trapped in the beam potential. The most relevant gases in the vacuum chamber are H_2^+ with $A=2$, CO^+ with $A=28$, and CH_4^+ with $A=16$, however CO_2^+ has $A=44$.

3. Trapping times

Ions can be created by different processes. Here we investigate the dominant effects: collision ionization, tunneling ionization, and ionization by synchrotron radiation.

We use the collision cross sections σ_{col} from [6]. This cross-section depends on the electron energies and in the range of $E_{low} = 10\,\text{MeV}$ and $E_{high} = 5\,\text{GeV}$ the cross-sections are specified in Table 1.

The time it takes to accumulate as many ions as electrons per length of the accelerator is given by $\tau_{col} = (\sigma_{col}\rho_{gas}c)^{-1}$, where the gas density is computed from the pressure, the Boltzmann constant and the temperature by $\rho_{gas} = p_{gas}/(k_B T)$. This time is also shown in Table 1. The ions that are needed to accumulate in the beam potential are therefore produced very quickly after the beam is switched on. Due to the difference in neutralization times, the neutralizing ion beam will mostly consist of H_2^+ ions.

Ions could also be produced by tunneling of the electrons from their orbit to a free state in the force of the electron beam. According to Eq. (3) in Ref. [7], the tunneling ionization rate is given by

$$W = 8\alpha^3 c k_{Ce}^2 \frac{\Delta E_{\text{ion}}}{F_{\max}} e^{-(4/3)\alpha k_{Ce}\frac{\Delta E_{\text{ion}}}{F_{\max}}} \tag{9}$$

Table 1
Collision cross-sections and neutralization times of dominant ions at ERL energies

Ion	σ_{col}, 10 MeV	σ_{col}, 5 GeV	τ_{col}, 5 GeV
H_2	$2.0\times10^{-23}\,\text{m}^2$	$3.1\times10^{-23}\,\text{m}^2$	5.6 s
CO	$1.0\times10^{-22}\,\text{m}^2$	$1.9\times10^{-22}\,\text{m}^2$	92.7 s
CH_4	$1.2\times10^{-22}\,\text{m}^2$	$2.0\times10^{-22}\,\text{m}^2$	85.2 s

where $k_{Ce} = p/\hbar$ is the Compton wave number, α is the fine structure constant, $\Delta E_{\rm ion}$ is the ionization energy, and $F_{\max}$ is the maximal force an electron in an atom can experience when it is close to the electron bunch. We use parameters from [7] to find the ionization energy of CO^+, i.e. $\Delta E_{\rm ion} = 11.21\,\mathrm{eV}$. And we use the force of Eq. (1) at a distance of $1\sigma_x$ from the beam center to estimate the maximum force in the electron beam as

$$F_{\max} \approx \frac{e^2}{4\pi\varepsilon_0}\frac{n_e}{\sqrt{2\pi}\sigma_s(\sigma_x+\sigma_y)}. \tag{10}$$

In all three working modes of the ERL the ionization time by tunneling is far longer than the bunch length, not allowing sufficient time for this ionization process.

Similarly, ionization by synchrotron radiation should not contribute significantly [7]. However, as mentioned above, scattering alone produces ions sufficiently quickly to have a negative influence on beam dynamics very quickly if no counter measures are taken.

4. Benefits from ion neutralization

For low beam energies, the Coulomb forces within the beam lead to nonlinear beam dynamics and emittance growth. The magnetic field of the beam creates a force that compensates the Coulomb expansion in the highly relativistic limit. However, the ion density $\rho_{\rm ion}$ produces only Coulomb forces and no magnetic field since the ions have no longitudinal velocity in a reasonable approximation. The total space charge force is therefore proportional to $\rho_e(1-\beta^2) - \rho_{\rm ion}$. When the ions fully saturate the electron beam, the electron density ρ_e in the center of a Gaussian bunch is related to the density of the ions by $\rho_e(0) = \rho_{\rm ion}(\Delta L/\sqrt{2\pi}\sigma_s)$. Having ions fully neutralize the electron beam therefore reduces the space charge force whenever $|1-\beta^2| > |1-\beta^2-\sqrt{2\pi}\sigma_s/\Delta L|$. The maximum energy where the neutralization by ions reduces space charge effects is determined by $\beta_{\max}^2 = 1-\sqrt{2\pi}\sigma_s/(2\Delta L)$. For operation modes (1) and (2) it is 8.4 MeV and for operation mode (3) it is 1.4 GeV.

When the beam is neutralized by ions, ion electron scattering can increase the emittance. The mean free path of an electron in the beam center is $\Delta l_{\rm col} = (\rho_{\rm ion}\sigma_{\rm col})^{-1} = \Delta L 2\pi\sigma_x\sigma_y/(n_e\sigma_{\rm col})$, which evaluates to 9.8 km for a neutralizing H_2^+ beam. In the few meters of the injector linac of an ERL before the energy of 8.4 MeV is reached, emittance growth due to electron–ion scattering is therefore not significant.

5. Ions in linacs

In a linear accelerator, the length of the electron-bunch train should be short enough so that optical errors due to the ions have not accumulated to an intolerable amount before the train has passed. To establish an estimate we allow a betatron phase error of 10% to accumulate. This error in phase advance is approximated [1] as

$$\frac{\Delta\phi_y}{\phi_y} = \frac{\int(1/pc)(\mathrm{d}F_y/\mathrm{d}y)\beta_y\,\mathrm{d}s}{\int\beta_y^{-1}\mathrm{d}s} = \frac{r_e}{\gamma}\frac{n_e\theta}{\Delta L}\frac{\langle\beta_y/(\sigma_y(\sigma_x+\sigma_y))\rangle}{\langle\beta_y^{-1}\rangle}. \tag{11}$$

For round beams with $\beta_x = \beta_y$ and $\varepsilon_x = \varepsilon_y$, this leads to a phase advance error of

$$\frac{\Delta\phi_y}{\phi_y} = \frac{1}{2}\frac{r_e}{\varepsilon_{yn}\langle\beta_y^{-1}\rangle}\frac{n_e\theta}{\Delta L} \tag{12}$$

where $\langle\cdots\rangle$ indicates an average along the beam pipe. For the operation modes (1) and (2) this amounts to $\Delta\phi_y/\phi_y = 73.3\theta$ and for operation mode (3) it amounts to $\Delta\phi_y/\phi_y = 0.15\theta$. For an error of $\Delta\Phi_y/\Phi_y \leqslant 0.1$, the degree of neutralization is $\theta = 0.1/73$ for mode (1) or (2) and $\theta = 0.1/0.15$ in mode (3). Using the above calculated time it takes ionization by collision to neutralize the electron beam, a phase advance change of 10% would occur in 7 ms for mode (1) and in 3.74 s in mode (3).

According to Ref. [1] it is a conservative estimate that ions clear the gap in $\tau_{\rm clear} = 2/f_p$ where f_p is the plasma frequency,

$$\tau_{\rm clear} = \frac{\pi}{c}\sqrt{\frac{2A_{\rm ion}\sigma_x\sigma_y\Delta L}{n_e r_p\theta}}. \tag{13}$$

In all operation modes the ion gap would have to be at least 31 μs long.

6. RF beam loading

While an ion clearing gap of 31 μs every 7 ms might be tolerable, there are RF beam loading effects which require that the beam current is not switched off instantaneously but slowly, and the clearing gap would have to be about 2 ms long.

The reason for this relative slow current ramp comes from an RF power drive limit. If the beam would be turned off instantaneously, the current stored in the machine would continue to pass through the main linac cavities, and depose RF power in the cavities. For a 100 mA beam current and a decelerating field of 16 MV per cavity, the deposed RF power per cavity would amount to $P = VI = 16\,\mathrm{MV}\times 0.1\,\mathrm{A} = 1.6\,\mathrm{MW}$. Avoiding beam induced field transients would require an equal amount of RF drive power from each main linac RF transmitter, which is more than a factor of 100 higher than the actual available RF power per cavity. Not compensating the RF power deposed by the beam would result in field amplitude transients

$$\Delta V = 2\frac{R}{Q}Q_L I(1-e^{-\omega_{1/2}\Delta t}) \tag{14}$$

where R/Q gives the strength of the coupling of the beam to the fundamental mode, Q_L represents the loaded quality factor of the fundamental mode, and $\omega_{1/2}$ is the half width half maximum bandwidth of the same mode. For a recirculation time of $\Delta t = 6\,\mu s$, $R/Q = 390\,\Omega$, and a beam current of $I = 0.1\,A$, the beam induced field transient is about 1.9 MV. This beam transient is not tolerable. The only alternative is to slowly ramp the beam current down and subsequently up again for each ion gap. With a 10 kW RF transmitter per cavity, the shortest possible clearing gap would then amount to about 2 ms

$$\Delta t_{\text{ramp}} = I\,\frac{V}{P_{\text{trans}}}\,\Delta t_{\text{rec}} = 0.1\,\text{A} \times \frac{16\text{MV}}{10\,\text{kW}} \times 6\,\mu\text{s} = 1\,\text{ms}. \tag{15}$$

However, having 2 ms clearing gap out of 7 ms is not tolerable for the synchrotron radiation users. It would not only significantly reduce the average beam current, but many fast experiments would have to gate data taking in order to take account for the ion clearing gap. The flux that would be available while the current is ramped down and up again during the 2 ms would not be usable since the beam size would change considerably during when the bunch charge changes during this time.

Gating data taking would be necessary in all experiments that want to follow (with time resolution) a process that extends somewhat over one ion clearing period. An example is X-ray crystallography where the rotation of the crystal takes at least many times 10 ms, during which many reflections are accumulated. The data gap caused by a beam gap could cause critical reflections to be lost since the rotation rates of the crystals are too high to easily allow start/stop of crystal rotation.

The fact that the beam size would change during the 2 ms gap would also cause problems for static, integrating measurements where the sample remains exposed to X-ray, accumulating radiation dose during the period of enlarged beam size, thus radiation sensitive samples would suffer more than without the gap. A rotating mechanical shutter could be used to gate the X-ray beam to avoid this problem.

These problems with X-ray experiments could, in principle, be resolved with advanced gating techniques. Our goal, however, is to build an ERL source which allows standard storage ring experiments to be performed with minimal modification to the experimental technique. Hence, below, we describe alternative ion clearing methods to accomplish this goal.

7. Ions in rings

The RF beam loading effects can be avoided when the clearing gaps of length L_g would be much shorter than one ERL circumference L_{erl} and would be separated by an integer fraction of this circumference. Then the gap in the accelerating beam would be simultaneously in the linac with the gap of the decelerating beam. The ERL cavities would therefore always have zero beam loading. One would now have to study which ions can be trapped by a beam potential that has gaps of length L_g. This analysis is similar to what has to be done for storage rings where short ion clearing gaps occur on every turn. As discussed in Section 2.1, the beam appears as a charged string to the ions for the operation modes (1) and (2). Therefore, we can describe the bunch train as one long bunch of length $L_{erl} - L_g$ and of charge $n_e\frac{L_{erl}-L_g}{\Delta L}$. Using Eq. (8), we find a requirement for L_g in order to avoid accumulation of ions,

$$(L_{erl} - L_g)L_g \leqslant \frac{A_{ion} 4\sigma_y(\sigma_x + \sigma_y)\Delta L}{n_e r_p}. \tag{16}$$

Experience has shown that choosing $A_{ion} \leqslant 44$ to avoid trapping ions as heavy as CO_2^+ is sufficient [5]. For the operation modes (1) and (2) this leads to $L_g \in [124\,m, 1376\,m]$.

However, this formula resulted from a small kick or thin lens approximation and is not very good when ions are not trapped and the kicks are therefore large. The focusing of ions in the electron beam can be described by a quadrupole matrix or a series of small kicks for each bunch in the train with ions freely drifting in the clearing gap. The trace of the matrix that describes one bunch train and one ion clearing gap has to be larger than 2 or smaller than −2 for ions not to be trapped.

Since the focusing force depends on the beam size, it varies substantially along the accelerator. Fig. 2 shows the trace of this matrix for CO_2^+ ($A = 44$) and for CH_4^+ ($A = 16$) for a vertical beta function $\beta_y \in [40\,m, 60\,m]$ and an average horizontal beta function of $\beta_x = 50\,m$. The clearing gap was assumed to be 500 RF buckets long.

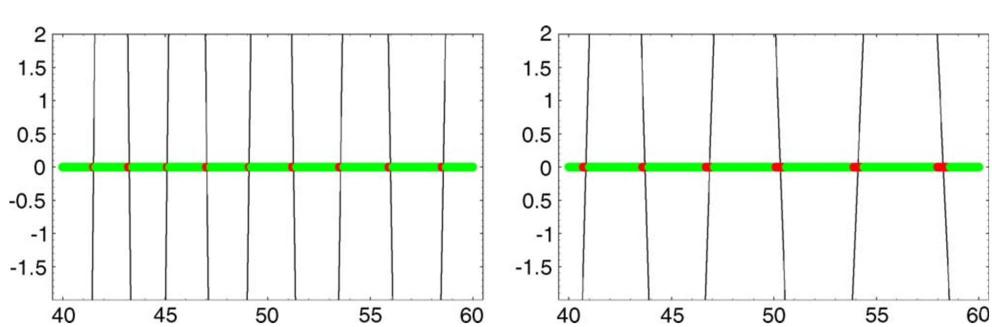

Fig. 2. Trace of the ion oscillation matrix for different β_y(m) for CH_4^+ (left) and CO_2^+ (right).

Over this limited change of beam size, ions rapidly change from being trapped to not being trapped in the electron potential. The regions in β_y where ions are trapped are smaller than about $\Delta\beta_y = 0.5\,\mathrm{m}$ and the regions along the accelerator where these ions are trapped are therefore quite short. If a waist at $\beta_y^* = 50\,\mathrm{m}$ is in the center of this region, its length would be $\Delta L_{\mathrm{ion}} = 2\sqrt{0.5\,\mathrm{m}\beta_y^*} = 10\,\mathrm{m}$. It is worth noting that for lighter ions and for smaller beta functions the sections are shorter. Since the velocity change in Eqs. (4) and (5) is inversely proportional to $A_{\mathrm{ion}}\sigma_y(\sigma_x + \sigma_y)$, also smaller electron emittances lead to shorter sections where an ion species can be trapped.

As described in the next section, the changing beam profile and the changing size of the vacuum chamber leads to a changing longitudinal beam potential and to a longitudinal force on ions. Ions will therefore not stay in each region where they can be trapped but will drift longitudinally into a region where they are not trapped. Therefore the short sections where ions can be trapped actually accumulate ions only if they contain a minimum of the longitudinal potential.

For a rough estimate we assume that a waist in the beam and also a minimum of the longitudinal potential only occurs approximately 4 times per betatron phase advance of 2π so that with Eq. (12),

$$\frac{\Delta\phi_y}{\phi_y} = \frac{r_{\mathrm{e}}}{2\varepsilon_{yn}}\frac{n_{\mathrm{e}}\theta}{\Delta L}\frac{4\Delta L_{\mathrm{ion}}}{2\pi}. \tag{17}$$

For the operating modes (1) and (2) this evaluates to $\Delta\phi_y = 19\phi_y$. An accumulation region of 10 m is therefore too long. Clearing gaps that are longer than the assumed 500 RF buckets of 0.4 μs would reduce this length. But this would become a significant fraction of the approximately 6500 buckets of the ERL circumference. Other ways of clearing ions out of accumulation regions will therefore be investigated below.

However, the presented estimate is probably very pessimistic since some of the accumulation points can be in regions where ions are not trapped, and since only vertical trapping forces were analyzed. This was done since the ion motion in the field of magnets tends to lead to ion trapping. But outside magnets, horizontal ion oscillations might not be stable in some of the regions where the vertical oscillations are stable.

While beam-loading in the main linac is eliminated by such clearing gaps, there would still be significant beam loading in the injection linac and in the electron gun. In contrast to the main linac, the installed RF power in the injector in principle allows to compensate beam transients from ion clearing gaps. However, the RF transmitters will have a finite bandwidth of several MHz, and thereby are limiting the rate at which the RF drive power can be ramped. The worst-case transients can be calculated from Eq. (14). For the injector cavity ($R/Q = 110\,\Omega$), the transient of a 0.4 μs ion clearing gap would be about 4%.

The transient effects in the electron gun occur because the power drawn from the HV power-supply varies between 75 kW and 0 from beam to clearing gap. This change in power cannot easily be achieved in one bunch gap of 0.8 ns. This problem would be eliminated if the clearing gap was produced by a fast kicker after the gun. Fast kickers with a rise time of below 0.8 ns would be required which have a flat top of about 0.4 μs and a very small amplitude after its excitation.

There are important X-ray experiments where even a short interruption of a few μs in the beam has disadvantages. An example is X-ray crystallography where a crystal is rotated in less than a second by about one degree to image reflections at many thousand lattice plains. Some reflections can illuminate their image point for very short times so that the recorded intensity is influenced by very short gaps in the beam.

8. Ion clearing electrodes

The above analysis has shows: (A) that ions in Cornell's X-ray ERL accumulate significantly quickly to cause problems, (B) ion clearing gaps after long bunch trains of about 7 ms have to be about 1 ms long to avoid RF beam loading effects, (C) short bunch trains of less than the ERLs length, i.e. about 6 μs, avoid beam loading in the main linac and require clearing gaps of about 0.4 μs length, which could not clear all relevant accumulation points of ions. Additionally, transient effects in the gun and the injection linac currently seem intolerable.

Therefore, ions have to be eliminated from the electron beam region by some other means. The only tested approach are electro-static clearing electrodes. They produce a DC electric field which is strong enough to draw ions out of the electron beam's potential. Since the electron beam is very narrow in the X-ray ERL, this potential is very steep and the required force is much larger than for other accelerators where clearing electrodes have been used.

Eq. (2) for the force on the electrons rather than on the ions evaluated at $y = 1\sigma_y$ leads to an approximation of the strongest attracting force of the accumulated ions on electrons creating a bending radius of

$$\rho = \frac{(\sigma_x + \sigma_y)\Delta L}{r_{\mathrm{e}}n_{\mathrm{e}}}. \tag{18}$$

For the three working modes this evaluates to modest curvatures with ρ being 1544 m, 4883 m and 345 313 m. The electric fields to overcome this force would have to be 150 kV/m, 50 kV/m and 0.7 V/m, respectively.

Since such clearing electrodes are hard to assemble along the complete accelerator, they have to be placed at those locations where longitudinal forces let the ions accumulate. The longitudinal forces are produce by changing electron beam profiles and by changing vacuum chamber dimensions. In first approximation, the ions accumulate at places where the electron beam is narrow, and where the grounded vacuum chamber is wide.

For this strategy to work, the time for ions to travel to the accumulation regions where the electrodes are located has to be significantly shorter than the beam neutralization time. To estimate this time, we assume round beams in a round beam pipe of uniform diameter. According to Ref. [8] the potential of a round uniform beam in a round grounded beam pipe is given by

$$V_0 = \frac{I}{\beta c}\frac{1}{2\pi\varepsilon_0}\left[\ln\left(\frac{r_0}{a}\right) - \frac{1}{2}\right]. \tag{19}$$

For a beam pipe radius of 4 cm and a low beta function of 1 m we obtain for the first and second operation modes 47 V.

Assuming that the beta function changes as in a field free region according to a parabola, one obtains that it takes only 0.4 μs for the ion to travel 3 m to the beam waist. Ions would therefore be cleared much more quickly than they are created by collisions.

Similar calculation are possible for a rectangular beam-pipe using formulas from Ref. [8, annex II] which is credited to Ref. [9].

9. Fast ion instability

During the short time it takes ions to move to clearing electrodes, the fast ion instability [10] has to be avoided. This instability arises from a magnification of random beam centroid oscillations by the increasing number of ions. In high current storage rings this instability can have a rise time of as little as several μs and could therefore develop before ions are eliminated by clearing electrodes. The characteristic timescale [11] of this instability is given by

$$\tau_{\rm fast} = \frac{1}{n^2}\frac{\gamma\sqrt{3\sigma_y(\sigma_x+\sigma_y)}^3\sqrt{A_{\rm ion}}}{4\rho_{\rm gas}\sigma_{\rm col}r_{\rm e}c\beta_y\sqrt{n_{\rm e}^3 r_{\rm p}\Delta L}}. \tag{20}$$

This refers to the nth bunch in a bunch train. The clearing time of 0.4 μs has passed after about 500 bunches; and for $n = 500$ we obtain for the X-ray ERL $\tau_{\rm fast} = 1$ ms. The characteristic time is therefore sufficiently longer than the cleaning time.

10. Experiences with ion clearing electrodes

In the 3.3 km long antiproton storage ring (Recycler) at FNAL there are close to 400 BPMs used as clearing electrodes, but problems with ion trapping nevertheless begin at about 2 mA coasting DC beam. At that point the emittance growth beyond what can be cooled with the stochastic cooling system. For a barrier-bunched beam with a several microsecond gap there are no problems with ions.

In the single pass DC electron beam at 4.3 MeV that is used for electron cooling of the antiprotons, ion accumulation begins at 10 mA currents. To control ions in the electron cooler, BPMs are used for which one button is at about 300 V and the other is grounded. The efficiency of this clearing method is not yet known [12].

In Ref. [13] experiences with the CERN electron–positron accumulator (EPA) are described. "In practice, even with a large number of electrodes, uncleared pockets always remain, and contribute to typical residual neutralizations of a fraction of a few per cent. No small electron storage ring exists which has reached a fully satisfactory ion-free situation, even with clearing electrodes." In the CERN antiproton accumulator (AA) a neutralization of below 1% were reached with clearing electrodes, but neutralization pockets still remained. It should be noted that, following from Section 5, 1% neutralization leads to a very strong optical error of about $\Delta\Phi_y/\Phi_y \approx 0.1$.

In the EPA, the AA, and other rings [13] shaking the beam has successfully been used to increase the effectiveness of clearing electrodes. While electrodes alone lead to a neutralization of 2–3% in the EPA, additional beam shaking reduced it to well below 1%. For this purpose a kicker is used that shakes the beam with a frequency that is on the one hand close to a revolution harmonic of the tune, creating small beam oscillations, and on the other hand close to the frequency with which ions oscillate in the beam potential, exciting large ion oscillations. Shaking alone is reported to be not as efficient. It is suspected that the clearing electrodes increase the longitudinal motion of ions. And for shaking to be effective, ions need to move longitudinally into a region where their oscillation frequency is in resonance with the shaking frequency.

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