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CONNECTING GAS-SCATTERING LIFETIME AND ION INSTABILITIES*

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Abstract

Recently there is a renewed interest in fast ion instability (FII) which is of concern for future low-emittance electron storage rings, such as MBA light sources and colliders, i.e. eRHIC. While analytical theories and numerical codes exist to model the effect, due to various assumptions and limitations, accurate experimental verification is often desirable. Unfortunately, one of the most critical parameters for FII (as well as the classical "trapped-ion" instability), the residual ion concentration, is usually the most uncertain. Vacuum gauges and residual gas analyzers (RGAs) provide some useful data, but they are often not accurate enough, and, more importantly, they cannot directly probe the ion concentration along the beam orbit. In this paper we show how one could use gas-scattering lifetime measurements to infer the residual gas concentration suitable for ion instability experiment modelling.

INTRODUCTION

The theory of fast ion instability and its first observations were reported more than 20 years ago [1-3]. As recent machine developments push for even lower emittances and higher currents, the instability is becoming more important for modern light sources and colliders. More recent observations at newly constructed light sources and low emittance storage rings can be found, for example in [4-9]. Several codes are reported to reproduce well the essential features of the instability [10-12]. Another code [13] is presently being developed for eRHIC [14], where ion instabilities could be of significant concern, because any coherent motion of the electrons will, via the beam-beam force, drive ion emittance growth. The goal of benchmarking this code at NSLS-II is what partially motivated this work.

A major difficulty in making quantitative comparison of the experimental results with the theory or with the tracking codes' predictions, is that one of the most critical parameters for the instability (as well as its classical, multi-turn, counterpart, "trapped-ion" instability), the residual ion concentration, is usually the most uncertain. For instance, theoretical predictions of FII based on linear response [1-2] predict transverse beam oscillation growth with time as $y \sim e^{\sqrt{t/t_c}}$ where the time constant is inversely proportional to the residual gas density. In a real machine, for a given vacuum system configuration, this density changes a lot along the beam path (due to varying magnetic fields, local pumping speed, local desorption rates, etc.), as well as with beam parameters and machine conditions.

Modern rings are equipped with a large number of vacuum gauges, but, by design, they cannot directly probe ion concentrations along the beam orbit. Finally, while elevated vacuum pressures at the gauge locations can generally be measured quite accurately, if the machine is well-conditioned, and the pressures are below ~1e-10 Torr, the accuracy often becomes much worse.

This is why we are investigating an alternative method to get an independent assessment of the residual gas pressure under conditions that are most relevant to FII experiments at NSLS-II. Gas-scattering is a relatively simple and well-understood process with the scattering rate directly proportional to the integral of residual gas density along the beam path. Our idea is to estimate these column densities from the gas-scattering lifetime. This is a work in progress and our initial goal is to show that the gas-scattering lifetime can be measured non-invasively, accurately and reliably under the conditions most relevant for FII experiments, and, in particular, when this lifetime is much longer than the Touschek lifetime.

BEAM LIFETIME BASICS

The mechanisms leading to lifetime losses in storage rings are well-known. Usually only two mechanisms need to be accounted for, gas-scattering and (typically dominant) Touschek scattering.

For constant gas pressure, gas-scattering lifetime results in the exponential time dependence of the total beam current,

$$I(t) = I(0)e^{-t/\tau_{gas}}, \tag{1}$$

where two separate processes are responsible for the decay. Elastic gas-scattering lifetime is given by [15]

$$\frac{1}{\tau_{gas\_el}} = \frac{2r_e^2 Z^2 \pi n c}{\gamma^2}\left[\frac{\langle\beta_x\rangle}{A_x} + \frac{\langle\beta_y\rangle}{A_y}\right], \tag{2}$$

where $A_{x,y} = \min_s(a_{x,y}(s)^2/\beta_{x,y}(s))$ are the horizontal and vertical acceptances, given by the minimum value of the aperture, $a(s)$, squared and divided by the beta function at that location, n and $Z \gg 1$ are the concentration and the atomic number of the residual gas ions, γ is the relativistic factor, and r_e is the classical radius of electron.

Lifetime due to inelastic gas-scattering, or Bremsstrahlung, is given by [15]

$$\frac{1}{\tau_{gas\_brem}} = \frac{16 r_e^2 Z^2 n c}{411} \ln\left[\frac{183}{Z^{1/3}}\right]\left[-\ln\varepsilon_{acc} - \frac{5}{8}\right], \tag{3}$$

where ε_{acc} is the limiting momentum acceptance.

Both gas-scattering lifetimes are inversely proportional to the ion density, and their effect can be combined in Eq. (1) by adding the rates,

$$1/\tau_{gas} = 1/\tau_{gas\_el} + 1/\tau_{gas\_brem}. \tag{4}$$

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During Touschek scattering process, electrons within a bunch collide with each other. The change in single bunch current, I_b, is therefore proportional to this current squared, which leads to non-exponential time decay,

$$I_b(t) = \frac{I_b(0)}{1+t/\tau_{tous}}, \quad (5)$$

where τ_{tous} is the so-called Touschek half-life (but also called Touschek lifetime), given by [16]

$$\frac{1}{\tau_{tous}} = \frac{\sqrt{\pi} r_e^2 c N_b}{\gamma^3} \left\langle \frac{C(\zeta)}{\sigma_x' V \varepsilon_{acc}^2} \right\rangle, \quad (6)$$

where N_b is the initial number of electrons per bunch, $C(\zeta) = -\frac{3}{2}e^{-\zeta} + \frac{\zeta}{2}\int_\zeta^\infty ln(u)\frac{e^{-u}}{u}\,du + \frac{1}{2}(3\zeta - \zeta\,ln\,\zeta + 2)\int_\zeta^\infty \frac{e^{-u}}{u}\,du$, $\zeta = [\varepsilon_{acc}/\gamma\sigma_x']^2$, V is the beam volume, σ_x' is the beam divergence and the brackets denote averaging over the ring.

When the fill pattern consists of equal bunches, we can write for the total current,

$$\frac{dI(t)}{dt} = -\frac{I(t)}{\tau_{gas}} - \frac{I(t)^2}{\tau_{tous}\, I(0)}, \quad (7)$$

which results in the current decay, due to both effects,

$$I(t) = I(0)\frac{\tau_{tous}}{(\tau_{gas}+\tau_{tous})e^{t/\tau_{gas}} - \tau_{gas}}. \quad (8)$$

LIFETIME MEASUREMENTS

We are not aware of any simple way of measuring individual lifetime components simultaneously. What is typically measurable from any beam intensity monitor, such as DCCT, is a total (linear) lifetime, $\tau(t)^{-1} \equiv \frac{1}{I(t)}\frac{dI(t)}{dt}$, which includes contributions from all loss mechanisms.

In principle, gas-scattering lifetime can be measured accurately if it could be made the dominant loss mechanism compared to the Touschek scattering. For instance, one could reduce the geometric acceptance with a scraper until Eq. (2) results in a much faster loss rate than Eq. (6). Separately, increasing the coupling would help by increasing the Touschek lifetime. Alternatively, one could measure the Touschek lifetime precisely by using a single- or a few-bunch fill pattern (e.g. [17]) with high single-bunch current, and potentially reducing the coupling and scanning the RF voltage, and then extrapolate the results to the high current and long bunch train(s) conditions relevant for FII experiments.

However, since our goal is to best estimate the gas pressure under the conditions needed for FII experiments (and without extrapolation from measurements at other machine conditions) these approaches are not very effective.

This is why here we attempt to measure the gas-scattering lifetime by directly fitting the current decay as given by Eq. (8), under the typical conditions of long high current bunch trains, low vertical emittance, and $\tau_{gas} \gg \tau_{tous}$.

Repeated measurements with this method were performed on multiple occasions, both with the storage ring in user operations (but with top off injection disabled), or in dedicated studies, and they all produced consistent results. The measurement we report here was performed on July 2, 2019. The ring was in "3 damping wiggler" operations lattice, with the standard fill pattern of 1200-bunch uniform train followed by an ion clearing gap (the NSLS-II ring harmonic number is 1320). A single "camshaft" bunch, used for the tune measurements with the transverse bunch-by-bunch feedback system, was in the middle of the ion gap, in the bucket 1280. Other conditions included in-vacuum ID gaps open, RF voltage at 1.5 MV (1.6% RF momentum acceptance) and HSX horizontal scraper brought in 5 mm away from the beam to define the acceptance.

A history plot of the relevant EPICS Process Variables (PVs) during the experiment is shown in Fig. 1.

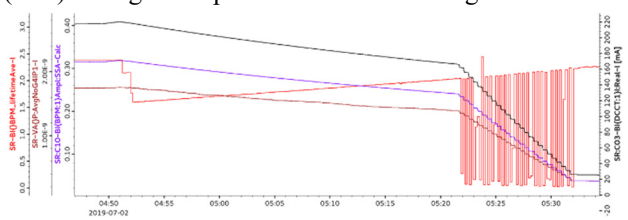

Figure 1: Beam current in mA (black, right axis), total beam lifetime in hours (red), ring-average gas pressure in nTorr (brown) and sum signal from BPM 10-1 (purple).

The data for the first part of the measurement were taken between 4:52 to 5:21 am, when the beam current decayed from 218 to 167 mA, while the total lifetime increased from 1.6 to 2.2 hours. (The right part of Fig. 1, with fast stepping-down of current will be addressed later.)

To find the gas-scattering lifetime from Eq. (8) we could directly fit DCCT-measured beam current, but instead, due to superior noise performance, we used the sum signal from one of the BPMs (purple trace in Fig. 1). This signal (re-calibrated to DCCT mA) is plotted in Fig. 2 together with 3 fits, given by Eq. (1) (i.e. gas only), Eq. (5) (Touschek only), and Eq. (8) (both effects). In the fits shown, in addition to the lifetime parameters, we fitted for the initial intensity. Separately we checked that not fitting for $I(0)$ but setting it to the value of the first data point did not change the result substantially. Even at this scale, the Eq. (1) exponential fit shows visible deviation from the data.

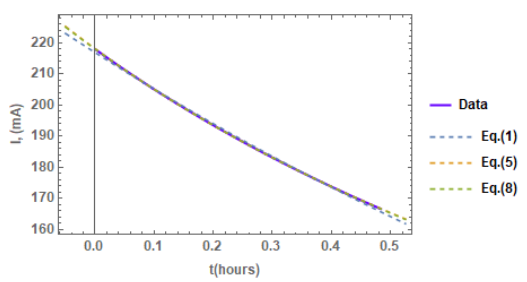

Figure 2: Measured BPM sum signal and 3 fitted models.

Fit residuals for the three models are plotted in Fig. 3.

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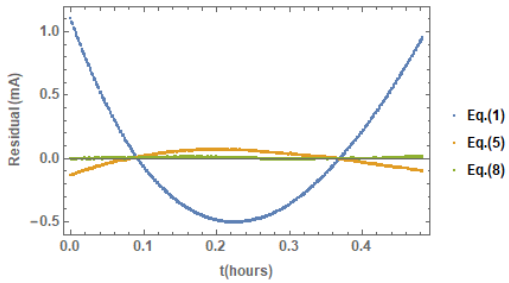

Figure 3: Fit residuals (the data minus the fitted model).

The Eq. (8) residuals show little systematic variation, suggesting that Eq. (8) is adequate.

The final gas-scattering lifetime value for the fitted model given by Eq. (8) is $\tau_{gas} = 16.664$ hours with a 95% confidence interval of {16.638, 16.688} hours. For the Touschek lifetime, the model gives $\tau_{tous} = 1.7629$ hours at 218 mA, with the interval of {1.7626, 1.7633} hours.

These results prove that with this method we can accurately measure the gas-scattering lifetime, even when it is significantly lower than the Touschek lifetime. We also emphasize that this method is non-invasive and requires no changes to the machine as long as it is in the decay mode.

To cross-check this method, immediately after these measurements and keeping the same machine conditions (and continuing with the electron bunch train which remained in the machine) we measured the lifetime with a different (and very invasive) method.

This time we used the cleaning feature of the DIMTEL transverse bunch-by-bunch (BxB) feedback system [18], to quickly shorten the bunch train, by killing 40 bunches at a time, starting from the head of the train. The resulting fill patterns, from the original 1200-bunch long one to the final of 200 bunches in duration, are shown in Fig. 4.

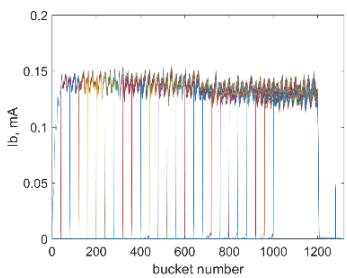

Figure 4: Fill patterns during the second experiment.

The corresponding reduction in beam current and ring-average vacuum pressure, as well as the changes in lifetime during this process are clearly visible in the right part of Fig. 1. At each fill pattern we stayed just long enough to reliably measure the total lifetime with the standard method used in operations, which fits the sum signal decay for a BPM over a predefined interval (set to 10 sec for this measurement), and then averages the result over 180 BPMs. Lifetime values measured during the time intervals when the BxB feedback system was kicking bunches out (resulting in very low values seen in Fig. 1) were discarded. The rest of them, circled for clarity, are plotted against the total beam current in Fig. 5 (left) together with the lifetime values from the first experiment.

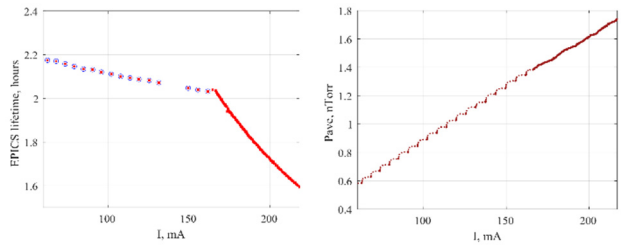

Figure 5: Total lifetime (left) and ring-average residual gas pressure (right) vs. beam current.

Also plotted is the average pressure from the vacuum gauges around the ring as a function of the beam current. The dependence is very close to linear, with the y-intercept (base-pressure) of only about 0.1 nTorr, much smaller than the pressure at high currents of say 100 mA or more. The same holds true for all of the individual gauges in the ring under all operating conditions (although the current slopes and small base-pressure values do vary with location).

For simplicity, we ignore this small base-pressure in comparison to the typical pressures at high current, i.e. assume $P(t) \sim I(t)$. This gives for the residual gas concentration, $n(t) \sim P(t) \sim I(t)$, and therefore, from Eqs. (2-4), $\tau_{gas} = \alpha / I(t)$, where α is a constant. We also ignore a small change in the Touschek lifetime during ~8 minutes when the current was reduced from 167 to 63 mA in Fig. 5 (per bunch current changed little). Because the total lifetime is $1/\tau = 1/\tau_{gas} + 1/\tau_{tous} = \alpha / I(t) + 1/\tau_{tous}$, eliminating τ_{tous}, from any two lifetime measurements in the 2nd experiment gives a value for α. The points, circled in Fig. 5, result, on average, in $\alpha = 3.06$ Amp-hours. This gives an estimate of gas-scattering lifetime at the end of the first experiment, at 167 mA, of 18.4 hours, which is about 10 % higher from the value obtained in from the fitted model in the first experiment. More detailed calculations, which approximately account for the small change in Touschek lifetime, bring the two values closer than 5% from each other. This gives us confidence that the first method reliably produces an accurate value for the gas-scattering lifetime.

DISCUSSION

From the obtained value of the gas-scattering lifetime and using Eqs. (2-3) one could straightforwardly extract a ring-average residual ion concentration if it were a single known ion species. To account for multiple ion species, we must rely on RGAs for the relative (but not absolute!) partial pressures. Presently, at NSLS-II, the RGAs indicate H2 to be the dominant gas, followed by CO, with a drop in partial pressure of about two orders of magnitude. Because for H2 one cannot use the $Z \gg 1$ assumption of Eqs. (2-3), we had to use more complicated expressions (see i.e. [19]). Our preliminary analysis, including only these two gas species, predicts the total ring-average pressure about a factor of two higher than the measured one shown in Fig. 5. We believe that the ion concentrations obtained by our method

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more accurately reflect the concentrations seen by the electron beam, so we will be using this method during our future ion instability studies.

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