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BEAM-BASED VACUUM MEASUREMENT AT THE FERMILAB RECYCLER RING

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Abstract

An analysis of the beam-based vacuum measurements was developed, which allows find the density of residual electrons, ring broad-band impedance and the average charge number of the residual nuclei. The method was applied to the data taken in the Recycler storage ring; the results are presented.

THE METHOD

There are three different phenomena leading to the evolution of the beam energy distribution: losses due to a real part of the ring impedance in the high-frequency range [1], the intra-beam scattering (IBS), and the ionization losses [2]. Each of these phenomena has its specific features allowing the extracting and quantifying of its contribution from the observed evolution of the energy distribution.

Up to frequencies as high as $\omega \approx \gamma c/a$, where a is the beam-tube aperture and γ the relativistic factor, the beam current has the Schottky noise spectrum. Due to the resistive (real) part of the longitudinal impedance in this frequency range, every proton loses the same amount of energy. These losses per proton are independent of the beam intensity, and are determined by the ring broad-band resistive impedance only [3]. *This results in a continuous shift of the energy distribution as a whole, without any change in its shape.*

The IBS, on the contrary, does not change the mean of the distribution. Instead, it results in the distribution widening. This widening has an important feature*: it preserves the mirror symmetry of the distribution*.

The ionization losses in the residual gas are described by the Landau distribution [2]. When used as a function of the energy offset from its average value, $x=E-\bar{E}(t)$, the Landau distribution function, $G(x,t)$, is highly asymmetric. *Asymptotically, it has a low-energy tail*

$$G(x,t) \sim \eta_L / x^2 ; \quad \eta_L \equiv 2\pi r_e^2 m_e c^3 n_e t , \qquad (1)$$

while its high energy tail is essentially zero. Here r_e and m_e are the electron classical radius and mass, and n_e is the density of electrons of the residual gas.

Assuming that the initial, $f_i(E)$, and the final, $f_f(E)$, distribution functions are known, the following analytic procedure applies.

First, the average losses, $\Delta\bar{E}$, resulting from the impedance and the ionization, are directly calculated from the measurements.

$$\Delta\bar{E} = \int E f_i(E) dE - \int E f_f(E) dE$$

When the energy offset is much higher than widths of the initial and final distribution, the asymptotic formula (1) is valid for the ionization-driven part of the evolution. Without IBS, the evolution of the distribution asymptotically might be presented as

$$\Delta f_- \equiv f_f(\bar{E}_f - x) - f_i(\bar{E}_i - x) = G(x,t) . \qquad (2)$$

Note that the impedance losses are included here through the mean energy shift $\bar{E}_f - \bar{E}_i$. Eq. (2) is supposed to be applied at the low-energy tail of the distribution. At the high-energy tail, nothing happens without the IBS, apart from the shift of the distribution as a whole:

$$\Delta f_+ \equiv f_f(\bar{E}_f + x) - f_i(\bar{E}_i + x) = 0 \qquad (3)$$

From Eqs. (2,3), an anti-symmetric evolution can be constructed:

$$\Delta f_a \equiv \Delta f_- - \Delta f_+ = G(x,t) \qquad (4)$$

The IBS gives its own contribution both for the negative and positive tail evolutions, Δf_{-IBS} and Δf_{+IBS}. However, the IBS works identically for them:

$$\Delta f_{-IBS} = \Delta f_{+IBS} .$$

That is why *IBS contributions are exactly cancelled in the anti-symmetric difference* (4). Thus, this difference shows the extracted contribution of the ionization in the evolution, regardless how strong are the IBS and the impedance losses.

The application of Eq. (4) allows calculate the density of residual electrons. After that, the ionization contribution in the mean energy loss can be calculated as

$$\Delta\bar{E}_{ion} = 2\eta_L \left[\ln\left(\frac{\gamma^2 m_e c^2}{I} \right) \right] ; \quad I \cong 10\,\text{eV} ,$$

while the impedance losses are given by the remaining part of the total losses:

$$\Delta\bar{E}_{imp} = \Delta\bar{E} - \Delta\bar{E}_{ion}$$

This allows us to estimate the associated broad-band impedance:

$$Z_{\parallel} / n \cong F Z_0 \frac{a^2}{r_e m_e c^3 \gamma^2} \frac{\Delta\bar{E}_{imp}}{t} \qquad (5)$$

where $Z_0 = 377$ Ohm; the form-factor $F \cong 1$ is determined by the impedance frequency dependence.

More information about the residual gas can be extracted from the transverse emittance growth rate:

$$\dot{\varepsilon} = 12\pi\Lambda c r_p^2 \langle\beta\rangle \sum_i n_i Z_i (Z_i + 1) / \gamma , \qquad (6)$$

where ε is the 95% normalized emittance, r_p is the classical proton radius, $\langle\beta\rangle$=30m is the ring-average beta-function, $\Lambda \approx 10$ is the Coulomb logarithm, and the sum is over the residual nucleus species with densities n_i and charge numbers Z_i. Taking into account that $n_e = \sum n_i Z_i$ and introducing the weighted average charge number as $\bar{Z} \equiv \sum n_i Z_i^2 / n_e$, the latter value is to be found from the emittance growth and the electron density:

$$\bar{Z} = \frac{\dot{\varepsilon}\gamma}{12\pi\Lambda c r_p^2 \langle\beta\rangle n_e} - 1 . \qquad (7)$$

The following describes the measurements procedure and results of the data analysis taken between August 2003 and June 2004.

MEASUREMENT PROCEDURE

Protons from the Main Injector were injected in four 2.5 MHz bunches inside of the Recycler barrier buckets. Once the beam was injected, the gain of the 2.5 MHz RF buckets was slowly lowered inside the barriers to zero, then the barriers themselves slowly decreased to zero. Measurements made after November 2003 included a step of turning off the high level RF amplifiers. The DC beam was then scraped with mechanical scrapers in both planes, to a half aperture of about 3mm (100% normalized emittance of 1.65 π-mm-mr), in consideration of the typical measured Recycler admittance of about 40 π-mm-mr.

TRANSVERSE EMITTANCE GROWTH RATE MEASUREMENT

The transverse emittance growth rates were measured with the 1.75 GHz slow wave Schottky detector [4]. The total transverse Schottky power, normalized to beam current, is proportional to the rms emittance, regardless of the transverse distribution function. The calibration of the Schottky power was performed separately by fully scraping the beam [5]. The emittance measurements were made every 15 minutes or so for about an hour, and linear fits were made to the data for the growth rate.

LONGITUDINAL ENERGY SPECTRUM MEASUREMENT

The conversion from the frequency to the momentum distribution was made using

$$\frac{\Delta p}{p} = -\frac{1}{\eta}\frac{\Delta f}{f} ,$$

where $\eta = -0.0085$ is the slip factor of the Recycler. The longitudinal frequency/energy spectrum of the DC beam was measured with both the 1.75 GHz slow wave Schottky detector in the sum mode, and the 79 MHz longitudinal Schottky detector [6]. The data from the 79 MHz Schottky detector exhibited similar qualitative behavior of distribution in time, as well as good agreement of mean energy decrease with the 1.75 GHz detector.

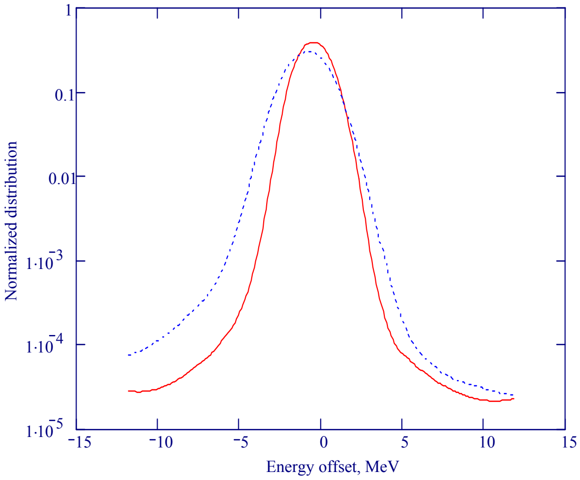

Figure 1. Recycler beam energy spectra of coasting beam separated by one hour measured on Aug. 2nd, 2003, log scale, 8.8E10 protons. Total broadening of the distribution is the result of intra-beam scattering (symmetric about mean) and multiple scattering (asymmetric about mean). Shift in mean is the sum of impedance energy loss and ionization loss.

DATA ANALYSIS

Data files of the longitudinal spectra separated by some time are analyzed. Figure 1 shows the energy spectrum separated by one hour taken on August 2nd, 2003, with 8.8E10 protons, prior to the shutdown, with the red trace being the initial distribution and the blue the final. Figure 2 shows the calculated asymmetry, based on the same data set as Fig. 1. Figures 3 and 4 are from the most recent data set, taken on June 24th, 2004, of 1.1E10 protons. In practice, the signal-to-noise ratio and the frequency resolution of the data contribute to the uncertainty in the measured ionization energy loss. Furthermore, the tail portion of the distribution exhibits larger deviation from the fit. This effect is understood as follows: the dynamic momentum aperture in the Recycler was measured to be about +/- 25 MeV, the effect of which was not simulated in the model. Particles with large momentum error can be lost due to chromaticity effects; in addition, particles with higher energy loss tend to have higher transverse betatron action, this effect should begin to become evident in the Recycler for $\Delta E > 6$ MeV based on kinematics, which is indeed observed in the data.

We assume that the total measured energy loss is the sum of ionization loss and impedance loss. The impedance loss is derived empirically by taking the difference between the total loss and the ionization loss. Further studies using this analysis with greatly improved accuracy will be pursued to better understand the broad-band impedance of the machine.

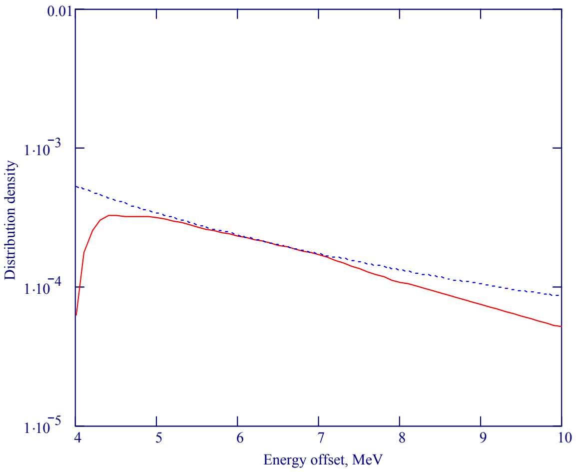

Figure 2. Asymmetry on log scale calculated from model (dashed) and the August 2nd data (solid). A single parameter, electron density, determines the shape of the tail and the asymmetric quantity as a function of energy offset.

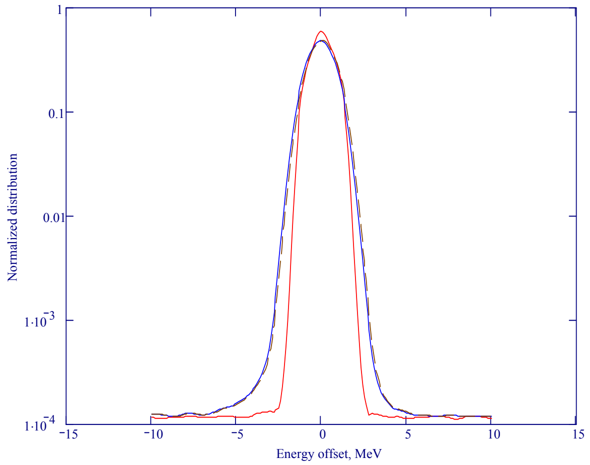

Figure 3. Data of longitudinal spectra of coasting beam separated by one hour taken on June 24th, 2004, log scale, 1.1E10 protons.

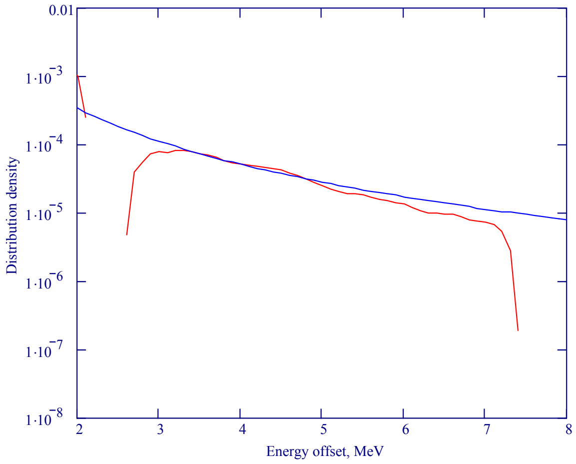

Figure 4. Asymmetry on log scale calculated from model and data from June 24th, 2004.

VACUUM PERFORMANCE

The total energy loss measured with the longitudinal Schottky spectrum was on the order of 0.5 MeV/hr in May 2003, with transverse emittance growth rate (normalized 95%) of over 10 π-mm-mr/hr. Immediately prior to the September 2003 shutdown and associated vacuum work performed on the Recycler, the beam lifetime measured with our standard procedure was about 90 hours. The transverse emittance growth rates were about 10 π-mm-mr/hr, the measured mean energy loss for one hour was 0.37 MeV, of which 0.18 +/- 0.03 MeV was determined to be ionization energy loss. The computed average pressure ($n_e kT/Z$) was about 0.6 +/- 0.2 nTorr, and the computed weighted charge number was 12 -/+ 2. Immediately after the shutdown, the measured beam lifetime was over 400 hours, transverse emittance growth rates were about 1 π-mm-mr/hr, the mean energy loss for one hour was about 0.2 MeV, of which about 0.026 +/- 0.008 MeV was determined to be ionization loss. Measurements have been repeated periodically since the shutdown. Data indicated that the vacuum performance has been improving over time. The most recent data (June 24th) showed transverse emittance growth rates of 0.7 π-mm-mr/hr, with a mean energy loss of 0.09 MeV per hour, of which 0.016 +/- 0.005 MeV was ionization loss, with an average pressure of 0.08 +/- 0.04 nTorr, and an average charge of 9 -/+ 3. This result is consistent with presently observed pressure [7].

SUMMARY

Beam based vacuum measurements for the Recycler has provided independent verification of the density and average charge of the residual gas in the Recycler beam pipe. An analysis has been developed to separate the effects of the broad-band impedance energy loss, intra-beam scattering and ionization energy loss. The data processed show a good agreement with the analytical fits.

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