ENERGY LOSS OF COASTING GOLD IONS AND DEUTERONS IN RHIC*

N. P. Abreu†, M. Blaskiewicz, K. Brown, J. Butler, W. Fischer,
M. Harvey, S. Tepikian, BNL, Upton, New York and
H. Burkhardt, CERN, Geneva, Switzerland.

Abstract

The total energy loss of coasting gold ion beams at two different energies and deuterons at one energy were measured at RHIC, corresponding to a gamma of 75.2, 107.4 and 108.7 respectively. We describe the experiment and observations and compare the measured total energy loss with expectations from ionization losses at the residual gas, the energy loss due to impedance and synchrotron radiation. We find that the measured energy losses are below what is expected from free space synchrotron radiation. We believe that this shows evidence for suppression of synchrotron radiation which is cut off at long wavelength by the presence of the conducting beam pipe.

INTRODUCTION

Synchrotron radiation is well known and measured for highly relativistic particles like electrons and positrons at several GeV, that is for Lorentz factors γ of the order of thousand. The spectrum is then dominated by hard ultraviolet or X-ray photons, see also Fig. 1, and emitted in the forward direction in a narrow cone of roughly $1/\gamma$ opening angle. In a ring with bending radius ρ, the total energy loss increases with E^4 with the beam energy E, or equivalently, the relative energy loss $\Delta E/E$ with γ^3, where γ is the Lorentz factor.

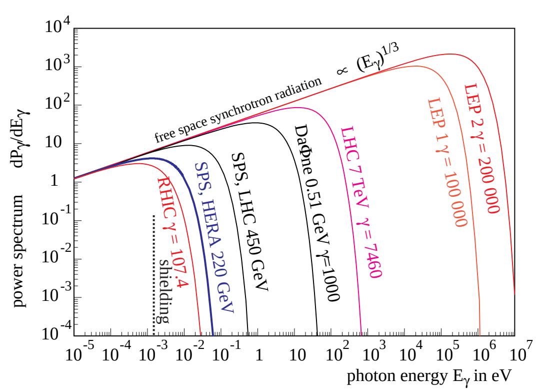

Figure 1: Calculated power spectra for synchrotron radiation.

The aim for this experiment is a measurement of the energy loss at moderately relativistic energies with γ of the order of hundred. The synchrotron radiation at these energies is dominated by rather soft photons, corresponding to wavelengths of the order of mm and emitted in a larger cone. Already in 1945, J. Schwinger predicted, that the low energy spectrum would be suppressed due to the presence of conducting material like the surrounding beam pipe [1].

The shielding of soft synchrotron radiation appears to be poorly known with little experimental data [2]. It is also of interest in the context of coherent synchrotron radiation for short bunches [3, 4].

Measurements of the total energy loss including synchrotron radiation of moderately relativistic protons and a single attempt with lead ions have been performed previously in the ISR [5], the SPS [6] and in HERA [7]. Beams were left coasting, with the radio frequency turned off. The energy loss of the debunched beam was observed as a shift in revolution frequencies on a longitudinal monitor. In both the SPS and HERA a clear increase of the energy loss with proton beam energy was observed, in broad agreement with the expectation from free space synchrotron radiation. The precision was not yet good enough to observe suppression effects. The SPS-measurements were limited in precision by a relatively poor quality and knowledge of the vacuum (of order 10^{-8} mbar). The HERA measurements were a first attempt just before the shutdown to upgrade to HERA II. Given the limited available time and non-optimal instrumentation, the results were quite encouraging. They showed a clear rise of the energy loss with beam energy in broad agreement with expectations from free space synchrotron radiation, but were not precise enough to draw any conclusions on suppression effects.

Measurements on heavy ions as are possible in RHIC gain in sensitivity from the ion charge. This allowed the first observation, to our knowledge, of suppression of incoherent synchrotron radiation.

KINEMATICS

A particle with charge q in a coasting beam has a change in revolution frequency (Δf) that is proportional to the change in the magnetic field (B) and in the particle momentum (p) and is described by the following expression

$$\frac{\Delta f}{f_0} = \alpha \frac{\Delta B}{B_0} - \eta \frac{\Delta p}{p_0} \tag{1}$$

where α in the momentum compaction factor and η the phase slip factor. In the case the magnetic field drift during the experiment is negligible the relative energy loss per turn, U, can be written as

$$U = \frac{E_0}{\eta f_0^2} \frac{df_0}{dt} \tag{2}$$

* Work performed under the auspices of the US Department of Energy.
† nabreu@bnl.gov

SYNCHROTRON RADIATION

The energy loss of a particle due to synchrotron radiation in free space is given by

$$U_s = \frac{q^2\beta^3\gamma^4}{3\epsilon_0\rho} \quad (3)$$

where $\beta = v/c$ and ρ is the field bending radius. For the case of RHIC the losses in free space are 4.95 eV/turn and 20.6 eV/turn for gold ions with energies of 70 and 100 GeV/nucleon respectively, and 3 meV/turn for deuterons at 101.9 GeV/nucleon. For these same energies and particles the suppression factor, due to the presence of the vacuum chamber walls, should be 94% for gold at 70 GeV/n and 56% for gold at 100 GeV/n for gold [6], and an almost total suppression for deuterons. In order to calculate the energy suppression we used a flat vacuum chamber, although in RHIC they are predominantly round.

IONIZATION OF THE RESIDUAL GAS

The energy loss due to ionization is characterized by the stopping power, the energy loss per unit distance, and it can be described by the corrected Bethe-Bloch formula [6].

$$\frac{dE}{dx} = -K_{BB}P_t m_t Z_t Z_i^2 \beta^{-1}\{11.1 - 0.9 ln Z_t + ln(\gamma^2 - 1)\} \quad (4)$$

here, x is the distance, P_t the partial pressure of the target ions, Z_t the atomic number, m_t the number of atoms/molecule, Z_i the atomic number of the incident particle and $K_{BB} = 0.0183$ eV/Torr/m. The composition of the residual gas is estimated to be 90% H_2 and 10% of heavier molecules like CO and the average pressure in the warm regions in RHIC is about 1 nTorr.

PARASITIC MODE LOSS

Each charge in the coasting beam produces an electric field which, by the relativistic contraction, is concentrated in the transverse direction with an opening of $\pm 1/\gamma$. It induces in the vacuum chamber wall a current pulse which, to a particle moving on axis of a perfectly conducting circular cylinder of radius b, is given by a Fourier-Bessel series [5] and has a rms width of

$$\sigma_w = \frac{b}{\sqrt{2}\gamma c} \quad (5)$$

The wall current will propagate through the vacuum chamber until any aperture change for bellows or other equipment interrupts its flow, at this point some energy is radiated away. There will be also an energy loss caused by the finite conductivity of the vacuum chamber walls. The role of the beam surroundings can be summarized by the impedance $Z(\omega)$ and the total energy loss can be written as

$$U = 2\int_0^\infty \widetilde{I(\omega)}^2 Re[Z(\omega)] d\omega \quad (6)$$

with the loss factor defined by

$$k_{rw} = -\frac{U_{rw}}{q^2} \quad (7)$$

In order to calculate this effect it is possible to identify two main contributions: the resistive wall effect and the diffraction contribution.

The resistive wall effect was estimated considering a stainless steel beam pipe with a radius of $b = 34.55$ mm and conductivity of $\sigma_{ss} = 2\times 10^6\ \Omega^{-1}m^{-1}$ in the cold region (2955 m long) and $b = 61.4$ mm and conductivity of $\sigma_{ss} = 1\times 10^6\ \Omega^{-1}m^{-1}$ in the warm region (879 m long). In this case we considered that the current excited by the beam have a Gaussian distribution with a rms width equal σ_w, so that the energy loss per turn could be approximated by [8]

$$U_{rw} = -\frac{Z^2e^2R}{4\pi^2 b\sigma_w^{3/2}}\Gamma\left(\frac{3}{4}\right)\sqrt{\frac{\mu_0}{2\sigma_{ss}}} \quad (8)$$

At high frequencies the impedance, due to the changes in the aperture, decreases as $1/\sqrt{\omega}$. To calculate the diffraction contribution we assumed that the impedance has a maximum around 3 GHz and $|Z/n| = 4\ \Omega$ and used a simple broad band model [9] to calculate the energy loss according to equation (6). The parasitic mode loss factor for each case is listed in Table 1.

RESULTS

In the experiment a beam was accelerated to the desired energy where it was debunched and left coasting. A longitudinal Schottky signal around $\omega_0 = 2\pi \times 78200$ s^{-1} (the revolution frequency) was observed and its central frequency was measured as a function of time for about 1 hour. From this the energy loss per turn was obtained, using equation (2). The shift of the revolution frequency line with time for the energies of 70 and 100 GeV/n are shown in Figure 2. The calculated value for the contribution of each effect which causes energy loss and the measured total energy loss with an estimated error ($U_m \pm \delta U_m$) are in Table 1. The drift of the magnetic field $\Delta B/B_0$ in 1 hour is estimated to be less then 10^{-5} hr^{-1} and contributes to an error of about 10% in the total energy loss. The expected and measured values for the total energy loss are close and most of the time within the error bar.

The two measurements for gold at 100 GeV/n were performed in two different runs (the first at Run07 and the second and shortest one at Run08) and show excellent agreement. The 70 GeV/n measurements were performed simultaneously in the two independent (so called yellow and blue) RHIC rings, again in excellent agreement. At 70 GeV/n, the contribution from synchrotron radiation is rather low allowing and mainly serves to check the impedance and gas contributions. In Table 1 the measured values for the 70 and 100 GeV/n for the gold ions is an average of the two measurements shown in Figure 2.

We also included results from measurements on deuteron ions for completeness. With only one charge compared to

Table 1: Estimated energy loss per turn and measured losses for Au^{79+} and deuteron ions at RHIC.

parameters	particle		Au^{79+}		d
	E_0	GeV/n	70	100	101.9
	γ		75.2	107.4	108.7
Synch. rad. free space	U_s	eV/turn	4.95	20.6	0.003
Synch. rad. reduced	U_s	eV/turn	0.3	9.1	0.0
Impedance	σ_w	mm	0.383	0.268	0.265
	k_{diff}	V/pC	4744	4777	4778
	k_{rw}	V/pC	230	394	401
	$U_{imped.}$	eV/turn	4.97	5.17	0.8×10^{-3}
Ionization	P	nTorr	1	1	1
	U_{ion}	meV/turn	9.3	9.7	9.7
Total Calculated	U_{total}	eV/turn	5.3	14.3	0.02
Total Measured	U_m	eV/turn	7	12	0.5
	δU_m	eV/turn	1	2	1

79 for gold ions, the sensitivity is much reduced and insufficient to draw conclusions.

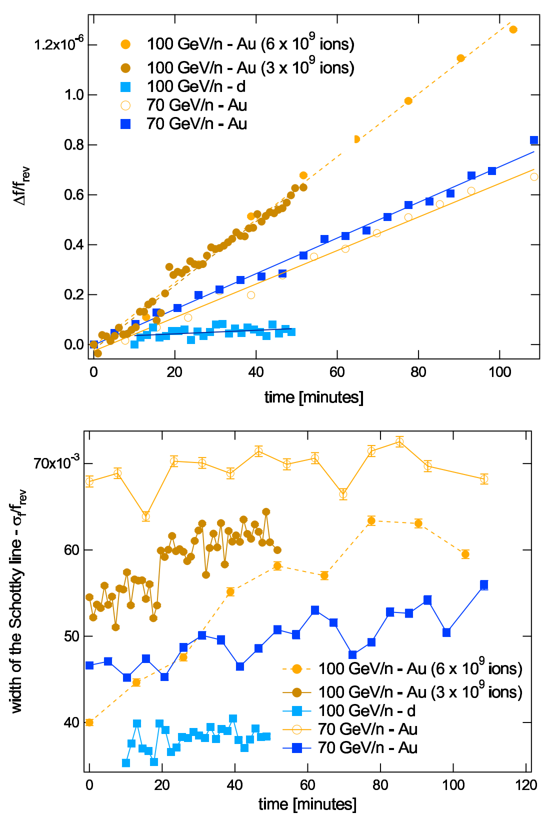

Figure 2: Measured shift and width of the revolution frequency line with time. Measurement of gold ions at 100 and 70 GeV/n and deuterons at 101.9 GeV/n.

CONCLUSION

We measured the total energy loss of ions in RHIC and compare this to the expected loss due to synchrotron radiation, impedance and gas ionization. For gold ions at 100 GeV/n the energy loss is dominated by synchrotron radiation and the measured energy loss is significantly lower than expected from free space synchrotron radiation. Measured and estimated energy loss per turn agree within 20% when a flat chamber geometry is used. To our knowledge, this is the first time that experimental evidence for the suppression of incoherent synchrotron radiation is observed. To confirm and improve these results, we plan further measurements at an intermediary energy, probably around 80 to 90 GeV/n and more detailed calculations on impedance and synchrotron radiation suppression.

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