Nuclear Instruments and Methods in Physics Research A ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Landau damping effects and evolutions of energy spread in small isochronous ring

Yingjie Li [a,*], Lanfa Wang [b], Fanglei Lin [c]

[a] Department of Physics, Michigan State University, East Lansing, MI 48824, USA
[b] SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA
[c] Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA

ARTICLE INFO

Article history:
Received 27 October 2013
Received in revised form
24 June 2014
Accepted 25 June 2014

Keywords:
Isochronous ring
Microwave instability
Space charge field
Landau damping
2D dispersion relation
Energy spread

ABSTRACT

This paper presents the Landau damping effects on the microwave instability of a coasting long bunch in an isochronous ring due to finite energy spread and emittance. Our two-dimensional (2D) dispersion relation gives more accurate predictions of the microwave instability growth rates of short-wavelength perturbations than the conventional 1D formula. The long-term evolution of energy spread is also studied by measurements and simulations.

1. Introduction

A coasting long bunch with high beam intensity in the small isochronous ring (SIR) at Michigan State University (MSU) demonstrates strong microwave instability with some unique properties that are different from the conventional ones [1–5]. For example, in the linear stage of the microwave instability, the instability growth rates are proportional to the unperturbed beam intensity I_0 instead of the square root of I_0 [2]. Pozdeyev pointed out that, in the isochronous regime, the radial coherent space charge fields of a coasting bunch with centroid wiggles may modify the slip factor, raise the working point above transition and enhance the microwave instability. This makes the instability growth rates linearly dependent on the beam intensity [3,4]. Another unique property is that the spectral evolutions of the line charge densities are not pure exponential functions of time, instead, they are often characterized by the betatron oscillations superimposed on the exponential growth curves. These betatron oscillations are the dipole modes in the longitudinal structure of the beam due to dipole moment of the centroid offsets [6].

Pozdeyev and Bi developed their own models and theories separately to explain the mechanisms of microwave instability in the isochronous regime [3–5], respectively. Their models use the 1D (longitudinal) conventional instability growth rates formula derived exclusively for a mono-energetic and laminar beam, in which the strong radial–longitudinal coupling effects in an isochronous ring are not included completely. This may overestimate the instability growth rates, especially for the short-wavelength perturbations, because the strong Landau damping effects caused by the finite energy spread and the emittance are all neglected. Though Pozdeyev explained the suppression of the instability growth of short-wavelength perturbations by the radial–longitudinal coupling effects qualitatively [4], no quantitative discussions on the Landau damping effects are available for a coasting bunch with space charge in the isochronous regime.

To predict the microwave instability growth rates more accurately, we introduce and modify a 2D dispersion relation with Landau damping effects considering the contributions from both the finite energy spread and emittance. By doing this, it can explain the suppression of the microwave instability growth rates of the short-wavelength perturbations and predict the fastest-growing wavelength.

This paper is organized as follows. Section 2 briefly introduces the small isochronous ring (SIR) at MSU and the simulation code. Section 3 discusses the limits of the conventional 1D growth rates formula, presents a modified 2D dispersion relation with Landau damping effects. Section 4 discusses the Landau damping effects in the isochronous ring by 2D dispersion relation. Section 5 presents the simulation study of microwave instability in SIR and provides benchmarking of the 2D dispersion relation with different beam

* Corresponding author.
E-mail address: liying.ji@msu.edu (Y. Li).

http://dx.doi.org/10.1016/j.nima.2014.06.070
0168-9002/© 2014 Published by Elsevier B.V.

parameters. Section 6 discusses the energy spread measurements and simulations for the nonlinear beam dynamics.

2. Small isochronous ring and CYCO

The National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University (MSU) constructed a low energy and low beam intensity small isochronous ring (SIR) to simulate and study the space charge effects in the high power isochronous cyclotrons [1,2] by scaling law. Its main parameters are shown in Table 1.

The small isochronous ring consists of three main parts: a multi-cusp hydrogen ion source, an injection line and a storage ring. There are four identical flat-field bending magnets in the storage ring. The pole face of each magnet is rotated by 26° to provide isochronism and vertical focusing at the same time. A pair of fast-pulsed electrostatic inflectors can kick the beam with the desired length into the ring. Since no RF cavity is utilized in the storage ring, the bunch can coast in the ring with a life time of about 200 turns. There is an extraction box located in one of the drift lines of the ring, in which a pair of fast-pulsed electrostatic deflectors can kick the beam down to the fast Faraday cup (FFC) installed below the median ring plane. The FFC is used to monitor the longitudinal beam profiles. The energy spread measurements can also be performed if we replace the FFC assembly by an energy analyzer assembly.

A 3D particle-in-cell (PIC) simulation code CYCO [1] was used to study the beam dynamics with space charge in the isochronous regime. It can numerically solve the complete set of equations of motions of charged particles in a realistic 3D field map with space charge fields included. Due to the large aspect ratio between the width and height, the storage ring vacuum chamber with rectangular cross-section is simplified as a pair of infinitely large conducting plates which is parallel to the median ring plane.

3. 2D dispersion relation

3.1. Limit of 1D growth rates formula

The conventional 1D growth rates formula for the microwave instability of a mono-energetic and laminar beam used in Ref. [4] is

$$\tau^{-1}(k) = \omega_0 \sqrt{-i\frac{\eta e I_0 k R Z(k)}{2\pi\beta^2 E}}, \tag{1}$$

Table 1
Main parameters of SIR.

Parameters	Symbol	Values
Ion species		H_2^+
Kinetic energy	E_{k0}	20 keV
Beam current	I_0	5–25 μA
Bunch length	L_b	15 cm–5.5 m
Betatron tunes	ν_x, ν_y	1.14, 1.11
Bare slip factor	η_0	2×10^{-4}
Circumference	C_0	6.58 m
Rev. period	T_0	4.77 μs
Life time		~200 turns
Beam radius	r_0	~0.5 cm*
Full chamber width	W	11.4 cm
Full chamber height	H	4.8 cm

* The beam radius r_0~0.5 cm is calculated from the algebraic matched-beam envelope equation (4.88a) and its solution Eqs. (4.93) of Ref. [7] for a typical beam of 10 μA, 20 keV, and 50π mm mrad.

where ω_0 is the angular revolution frequency of the on-momentum particles, $\eta = \alpha - 1/\gamma^2$ is the slip factor, α is the momentum compaction factor, γ is the relativistic energy factor of the on-momentum particle, e is the electron charge, I_0 is the unperturbed beam intensity, k is the perturbation wavenumber of the longitudinal charge density, R is the average ring radius, $Z(k)$ is the longitudinal space charge (LSC) impedance, β is the relativistic speed factor, E is the total energy of the on-momentum charged particle. Essentially, the 1D dispersion relation (23) of Ref. [5] is the same as the 1D growth rates formula (1), if we express the longitudinal electric field by the LSC impedance.

If the transverse dimension of a vacuum chamber is much greater than the beam diameter, the image charge effects of the chamber wall can be neglected in the short-wavelength limit [8–10]; therefore, the longitudinal monopole mode space charge impedance $Z(k)$ of a circular beam can be approximated from the on-axis space charge field as [4]:

$$Z(k) = Z_{0,sc}^{\parallel}(k) = i\frac{2Z_0 R}{k\beta r_0{}^2}\left[1 - \frac{kr_0}{\gamma}K_1\left(\frac{kr_0}{\gamma}\right)\right], \tag{2}$$

where $Z_0 = 377\ \Omega$ (ohm) is the impedance of free space, r_0 is the beam radius, $K_1(x)$ is the modified Bessel function of the second kind.

For a coasting long bunch with strong space charge effects in the isochronous ring, the longitudinal space charge fields may induce the coherent energy deviations and the associated radial offsets of the local centroids. Consequently, there are centroid wiggles along the bunch. Assume the longitudinal distribution of the radial centroid offsets is a sinusoidal function of the longitudinal coordinate z with a wavenumber k_c, in the first-order approximation, we can choose $k \approx k_c$ and use the same k in the expressions of $\eta(k)$ and $Z(k)$ in Eq. (1) just as treated in Ref. [4] (please check Eqs. (2), (12), (13), and (14) in Ref. [4]). Then η may be approximated by the space–charge modified coherent slip factor $\eta_{sc}(k)$ as [3,4]

$$\eta \approx \eta_{sc}(k) = \frac{eI_0}{2\pi\varepsilon_0\gamma m_{H_2^+}\omega_0{}^3 r_0^2 R}\left[1 - \frac{kr_0}{\gamma}K_1\left(\frac{kr_0}{\gamma}\right)\right], \tag{3}$$

where $m_{H_2^+}$ is the rest mass of H_2^+ ion, $\varepsilon_0 = 8.85\times10^{-12}$ F/m is the permittivity of free space. Note the relativistic factor γ is introduced in Eq. (3) to make the original expressions of $\eta_{sc}(k)$ in Refs. [3,4] compatible with the high energy beams.

The LSC impedance in Eq. (2) is evaluated from the 1D space charge field model on the beam axis. While Venturini [11] pointed out that the granularity of the beam distribution in transverse plane may induce the transverse field fluctuations (shot noise). The transverse field fluctuations may translate into the longitudinal fluctuations of the electric field making the 1D field model invalid when perturbation wavelength is smaller than $2\pi r_0/\gamma$ or $kr_0/\gamma > 0.5$. In addition, the off-axis LSC field is always weaker than the on-axis LSC field within the beam radius. Both of these 3D effects should be taken into account in the accurate evaluation of the LSC impedance. Ratner [12]studied the above 3D space charge effects and found that, instead of the on-axis LSC field, if the mean LSC field averaged over the cross-section of a round beam with uniform transverse density is used, the 1D and 3D field models give nearly identical LSC fields. The formula for the average LSC impedance is [13]

$$Z(k) = Z_{0,sc}^{\parallel}(k) = i\frac{2Z_0 R}{k\beta r_0{}^2}\left[1 - 2I_1\left(\frac{kr_0}{\gamma}\right)K_1\left(\frac{kr_0}{\gamma}\right)\right], \tag{4}$$

where $I_1(x)$ is the modified Bessel function of the first kind. It is believed to be a more accurate description of the collective LSC effects than the conventional one in Eq. (2) in the short-wavelength limits.

Please cite this article as: Y. Li, et al., Nuclear Instruments & Methods in Physics Research A (2014), http://dx.doi.org/10.1016/j.nima.2014.06.070