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Two-Beam Instability in Electron Cooling

A. Burov
Fermi National Accelerator Laboratory, Batavia, IL 60510

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Abstract

The drift motion of cooling electrons makes them able to respond to transverse perturbations of a cooled ion beam. This response may lead to dipole or quadrupole transverse instabilities at specific longitudinal wave numbers. While the dipole instabilities can be suppressed by a combination of the Landau damping, machine impedance, and the active damper, the quadrupole and higher order modes can lead to either emittance growth, or a lifetime degradation, or both. The growth rates of these instabilities are strongly determined by the machine $x - y$ coupling. Thus, tuning out of the coupling resonance and / or reduction of the machine coupling can be an efficient remedy for these instabilities.

1 Introduction

Electron cooling is an effective method to increase phase space density of hadron beams. Since its invention by G. I. Budker [1], and experimental proof at NAP-M [2], it has been successfully used at many non-relativistic ion storage rings (see e. g. [3], [4]), and recently 8.9 GeV/c antiprotons have been electron-cooled at Recycler ring, Fermilab [5]. To cool the ion beam in a storage ring, it is merged with the a comoving electron beam in a part of the ion orbit. Cooling results then from a thermal flux from the hot ions to the cold electrons. Normally, the ion beam does not need focusing elements inside the cooler, while the electron beam is focused by a homogeneous solenoidal magnetic field.

Being able to make beams brighter, electron cooling brings specific problems for the cooled beams as well. First of all, electron cooling, as any cooling, makes the cooled beam less stable against any kind of coherent motion [6], would it be driven by an impedance of the chamber, or by a stochastic cooling system, or by a structure resonance of space-charge shifted envelope modes [7]. All these issues are out of scope of this paper, devoted to analysis of coherent interaction of the cooled (ion) beam and the cooling electron beam.

The cooling effect is caused by interactions of ions with single-particle, or microscopic fields of the electron beam. However, macroscopic fields of the electron beam act on the ions too, and this interaction can cause damage to the cooled beam. In principle, the situation here is similar to beam-beam effects in colliders, where the beam-beam effects are classified as either incoherent (weak-strong) or coherent (strong-strong) ones.

A tune shift by the space charge of the electron beam drives high-order resonances in the ion motion, and this incoherent effect may reduce a lifetime of the ions. This effect was first pointed out by D. Reistad [8], who suggested that as an explanation for reduction of the ion life time with the electron current, observed at CELSIUS ring [9], and called such kind of phenomena as "electron heating". Theoretical and numerical analysis of this incoherent beam-beam effect for CELSIUS parameters was given in Ref. [10]. Another possibility for incoherent beam-beam interaction could be an excitation of the ion oscillations by a noise of the electron beam at the betatron side-bands of the ions; influence of a noise of the electron current is estimated in Ref. [11]. Some coherent ion-electron interaction seems to be responsible for the lifetime reduction observed at several coolers, according to V. Parkhomchuk [12], [13]. Recent empirical data on various beam-beam effects can be found in Ref. [14].

Coherent ion-electron interaction was theoretically considered in a model of transversely immobile, totally magnetized electrons [15]; the longitudinal and the transverse impedances introduced by the electron beam were calculated. These impedances appeared to be too low for realistic parameters of electron coolers,