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Halo Generation and Beam Cleaning by Resonance Trapping*

Alex Chao, Stanford Linear Accelerator Center, Stanford, California

Abstract

One of the mechanisms of halo generation occurs when particles are trapped by a nonlinear resonance $\nu \approx m/p$ as the tune ν is being modulated. This note is intended to renew some attention to this mechanism, and hopefully to trigger new study to understand it more quantitatively. This same mechanism used in reverse could serve to clean beam halos and to relax requirements on the collimators.

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1 Halo Mechanism

It was proposed that beam halos can be generated in a high-intensity storage ring by way of a particle trapping mechanism due to a modulating nonlinear resonance [1, 2]. A survey of this mechanism in relation to other nonlinear resonance effects has been made in [3, 4, 5], although a systematic quantitative evaluation of the resonance trapping mechanism to the application of halos seems not yet available. The hope of this note is to renew some attention to this halo generation mechanism.

In this mechanism, the tune of the accelerator is close to a nonlinear resonance $\nu \approx m/p$. The resonance will generate islands in the 2-D phase space. (We here consider 1-D dynamics only.) If the tune of a particle ν is slowly modulating in time, the islands will move in the phase space. They will move towards the phase space origin as ν approaches the resonant value m/p and away from the phase space origin as ν moves away from m/p. As the tune modulates, the islands therefore move in and out in phase space. The speed at which they move is determined by how fast the tune modulates. In addition to the location of the islands, the island area also changes as the tune changes.

One reason the tune might be modulating is through synchrotron oscillation. If the storage ring has a finite chromaticity, a particle's tune will oscillate as its energy executes synchrotron oscillation. Another possible reason is power supply ripple causing the tune to oscillate. One might also imagine other possible reasons such as quantum radiation diffusion or intrabeam scattering although in that case the tune does not oscillate but wonders around when the particle energy wonders in random walks and the storage ring has a finite chromaticity.

As the islands move in and out in phase space, they may trap particles and carry the trapped particles with them as they move. The trapping efficiency, $\eta_{\rm trap}$, a key quantity to be considered, depends on the island area A and the island moving speed S. In fact, we may loosely write[†]

$$\eta_{\rm trap} \sim A\, e^{-S}$$

Larger islands trap more particles, while islands moving too fast become ineffective traps. In fact, trapped particles may leak out of the islands if the islands move too fast, i.e. the islands become "leaky".

One possible halo generation mechanism therefore occurs as follows. As the tune modulates and the islands move in and out in phase space, the islands will be able to carry particles from small amplitudes to large amplitudes, and vice versa. However, if the islands have a greater trapping efficiency when they are closer to phase space origin (ν is closer to m/p) than when they are away from phase space origin (ν is away from m/p), then the modulating islands will act as a pumping mechanism to carry particles systematically from the beam core to the beam tail. The pumping rate is proportional to

$$\nu_{\rm mod}\,[\eta_{\rm trap}(core) - \eta_{\rm trap}(tail)]$$

[†]The actual formula is more involved. For one special case, see [2].

where $\nu_{\rm mod}$ is the tune modulation frequency. A more quantitative analysis of this pumping rate is yet to be invented and carried out, although useful references exist, e.g. [3, 4, 5, 6].

One might also envision an emittance dilution mechanism if $\eta_{\rm trap}(core) < \eta_{\rm trap}(tail)$. In this case, the empty island buckets are brought into the beam core as empty filaments, not unlike the mechanism of phase displacement acceleration [7]. This effect however probably dilutes the effective beam core rather than causing a beam halo.

One might envision two qualitatively different types of nonlinear resonances as far as resonance trapping is concerned. One type, caused by head-on beam-beam or space charge effects, has the property that the driving force tends to decrease as the particle moves far into the beam tail. For the other type, caused by magnet nonlinearities or long-range beam-beam effects, the force tends to increase as the particle moves far into the beam tail. One would expect different halo generation behavior in these two types of nonlinear resonances.

2 Beam Cleaning

It turns out that the resonance trapping mechanism can in principle be used to clean the beam tails [8]. To do so, we will consider purposely modulating the tune in a pre-programmed manner, with the aim of bringing particles with modest amplitudes (particles to be cleaned) all the way out of the beam and into a collimator. In this application, the nonlinear resonance is used similarly to beam extraction [9, 10]. This arrangement of dynamic beam cleaning may be useful to avoid having collimators very close to an intense beam core. For application to storage ring colliders, whether a strong beam-beam interaction would dominate the phase space topology, and therefore ender the resonance trapping ineffective, is one issue of concern, unless the beams are separated during cleaning [11].

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