Space Charge Compensation (SCC) in Hadron Beams

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1. Longitudinal SCC: Inductive Inserts

Longitudinal space-charge fields can generate substantial distortion of the rf-generated potential wells, fill the extraction kicker gap in the beam, affect the incoherent synchrotron tune spread, and have the potential for causing instability and longitudinal emittance growth. The net effective voltage per turn resulting from the space-charge self voltage and the ring inductive wall impedance $\omega_0 L$ is proportional to the slope of the beam current distribution $e\beta c\, \lambda(s)$ and can be expressed as:

$$V_s = \frac{\partial \lambda(s)}{\partial s}\left[\frac{g_0 Z_0}{2\beta\gamma^2} - \omega_0 L\right] e\beta c R$$

where $R=c/\omega_0$ is the average machine radius, Z_0=377 Ohm and $g_0=1+2ln(b/a)$ is the geometric space-charge constant , a and b are the beam radii and vacuum-chamber aperture. By introduction a tunable inductance L, e.g. of ferrite rings, the term in brackets and, consequently, the space-charge effect may be substantially reduced or canceled at some chosen energy [1].

This concept has been experimentally proven at the LANL Proton Storage Ring at LANL where three inductive inserts, each consisting of 30 “cores” of a cylindrically shaped ferrite with thickness of 1 inch, inner diameter of 5 inches, and an outer diameter of 8 inches, were installed. . The magnetic permeability of the ferrite could be adjusted by introducing current into solenoids wound around the ferrite so that in the MHz range of frequencies the longitudinal space charge impedance of the machine was compensated [2]. A strong longitudinal instability was noticed at much higher frequencies of about 75 MHz, but it was later suppressed by heating the ferrite to a temperature of 130◦C to make it more lossy.

The inserts have proven beneficial in raising the threshold for the two-stream e-p instability at PSR (Fig.1) and achieving shorter bunch length.

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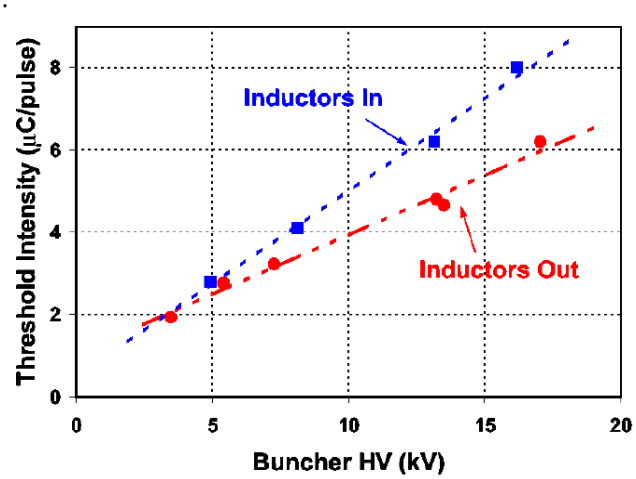

Figure 1: PSR e-p instability threshold vs rf buncher voltage with and without the inductive inserts.

Operated by Fermi Research Alliance, LLC under Contract No. De-AC02-07CH11359 with the United States Department of Energy.

2. Transverse SCC

There are several methods to compensate transverse s.-c. effects which often manifest themselves in the form of beam loss, core emittance growth, and halo formation.

In the case of **passive neutralization,** the s.-c. force of a proton beam can compensated by ionization electrons, electron cloud, or negative ions which are approximately at rest longitudinally, but move transversely during the beam passage. The compensation condition reads $\eta \approx 1/\gamma^2_p$. Neutralized low energy beams of heavy ions have successfully transported in a number of linear accelerators [3]. A factor of 9.5 increase of the maximum circulating beam current above (coherent) s.-c. limit was achieved at the Novosibirsk 1 MeV proton ring by increasing the residual gas pressure in excess of 10^{-4} Torr and accumulation of ionization electrons [4]. The beam lifetime was very short and transverse and longitudinal proton distributions not well controlled.
Optimum compensation requires that the transverse electron and beam distributions are matched. That could be achieved by confining the electrons transversely with strong solenoid fields to "columns," and using electrostatic electrodes to fine tune the charge density [5]. Strong magnetic field also stabilizes electron "column" motion and prevents coherent e-p instability. Simulations show significant reduction of s.-c. induced emittance growth with only few "columns" occupying a small fraction η of the ring circumference [5].

Electron lenses, in which externally generated electron beam with matched transverse distribution collides with the proton beam inside a strong solenoid field, could also compensate the s.-c. tune shift [6]. Assuming the total length of the lenses L, distributed around the ring, and an electron beams co-propagating with the proton beam, the electron current needed per lens is [6] $J_e = (B_f \kappa e c N_p/L)\, \beta_e/(\gamma^2_p\,(1 - \beta_p\beta_e))$, and for many accelerators of interest lays in the range of 1-10A for 10-40 keV electrons (here κ denotes the degree of compensation, B_f – proton bunching factor). These parameters are close to those of the operating Tevatron electron lenses. The SCC by lenses works better if the electron current is modulated to match longitudinal profile of proton bunches [7].

Passive cancellation of the next-to-leading term in the s.-c. force is possible by **octupole** fields. For a round beam, the 4th order of term of the direct s.-c. potential varies as $(x^4 + 2x^2y^2 + y^4)$, while the potential of an octupole is proportional to $(x^4 - 6x^2y^2 + y^4)$. Therefore, at least two families of octupoles are needed to reduce the s.-c. tune spread, which are placed at locations with either peak and intermediate values of the beta function, respectively. The beta functions should sufficiently vary over the length of an optical cell, e.g., by a factor 2 or more.

Pole-face windings allow precise adjustments of the tune shift with transverse position up to a high order. At the CERN ISR, 24 pole-face windings modifying the local magnetic field were used to correct the horizontal and vertical indirect s.-c. tune shift plus the next 4 orders in their Taylor expansions with respect to the horizontal position. The correction increased the maximum ISR beam current 15 times [8].

Recently proposed **fully nonlinear lattice** accelerators have promise to accommodate extraordinary large tune spreads in circulating beams without driving losses (resonance free optics) [9]. Numerical studies of s.-c. dynamics in such rings have been started.

References:

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