POSSIBLE COMPENSATION OF LONGITUDINAL SPACE-CHARGE FORCES IN THE CPS AT TRANSITION

by

Kjell Johnsen

Near transition the motion of particles within the bunches is non-adiabatic. With proper passing of the transition the bunches nevertheless come into the adiabatic region again properly matches to the buckets and with no increase in effective phase space area. This comes from the fact that the passing of transition is symmetric in the sense that the particle trajectory is the same whether one looks forward or backward in time from the transition point.

With longitudinal space charge forces present this symmetry is spoiled, and one must expect blow-up. A moderate blow-up in the CPS does not result in beam loss, but since it always causes a decrease in the effective phase space density the effect is harmful to the ISR long before a beam loss is observed. There are, however, various ways of restoring symmetry, at least to the linear approximation, and a few examples will be given in the following.

1. Change of RF Amplitude and Phase to Restore Symmetry

We assume a phase angle $\varphi_{s0}$ with no space charge and $\varphi_{s1}$, 2 with space charge, index 1 and 2 referring to before and after transition respectively. We assume the space charge force to be $\eta$ times the RF restoring force with no space charge present. To keep the restoring force unchanged with space charge, we require (with phase angle measured from the peak of the wave):

a) Before transition:

$$\tan \varphi_{s1} = (1 + \eta) \tan \varphi_{s0}$$
b) After transition:
\[ \tan \varphi_{s2} = (1 - \eta) \tan \varphi_{s0} \]

One notices two things. Firstly, the stable phase has to be programmed according to intensity and bunching at a given moment. Secondly, the phase jump at transition is not from \( \varphi_{s0} \) to \(- \varphi_{s0} \) as with no space charge, but from \( \varphi_{s1} \) to \(- \varphi_{s2} \).

The voltage has to change in the following way:
\[ \hat{V} = \frac{\cos \varphi_{s0}}{\cos \varphi_{s}} \hat{v}_{o} \]

and at transition the voltage will have to make a jump given by
\[ \hat{V}_{1} - \hat{V}_{2} = \hat{v}_{o} \cos \varphi_{s0} \left( \frac{1}{\cos \varphi_{s1}} - \frac{1}{\cos \varphi_{s2}} \right) \]

2. Separate RF System to Restore Symmetry

To control from the beam intensity the phase-stationary point, the voltage and the jump of both these quantities at transition complicates the main RF system unduly. We shall therefore look at the advantages that a separate compensating RF system might offer. Such a system would only have to be on for a short while around transition, and it will therefore require only a small frequency swing. Further, it will have its zero crossing at the bunch centre and with a force constant opposite that of the space charge. Its phase can therefore always be controlled by the phase lock system with no jump at transition. It will also have no amplitude jump at transition, only a smooth variation given by the variation of \( \eta \), and a pulse to pulse variation given by the beam intensity variations.

The restoring force of the main RF system can be written
\[ -\hat{V} \sin \varphi_{s} \]

and with the previous notation we therefore write for the beam restoring force
\[ \eta \hat{V} \sin \varphi_{s} \]

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We assume that the compensating system works on the n-th harmonic of the main system. Its restoring force at the zero crossing of its voltage is in the same units

\[^n \frac{V}{n}\]

and therefore the condition for space charge compensation is

\[\frac{\hat{V}}{V} = \frac{\eta \sin \varphi}{n}\]

As noticed the required voltage is inversely proportional with the harmonic number, which indicates an advantage in going to high harmonics. One should, however, not go so high that non-linearities in the buckets become important.

3. Compensation by Mis-Timing

There is a possibility of compensating for some of the effect of the asymmetry by mistiming the transition jump. This method does not seem to have enough variables to change both the shape and the orientation of the phase-space ellipse of the bunch, and can therefore only give partial compensation. It might, however, be used together with method 1 to reduce the requirements to that method.

Mistiming has been tried on the CPS with only moderate effects.

4. Ducking-Under at Transition

The method of ducking under at transition was proposed long ago by Courant. It has the advantage of making it possible to keep the phase extension of the bunch large. It is therefore not a compensation of space charge forces, but a way of reducing them. The RF restoring force is, however, also reduced and the net result may not be beneficial. It has the further disadvantage of making the forces on the bunch very non-linear in the neighbourhood of transition. This, however, may not be too harmful since the particles are very "stiff" anyway in this region. The method
is simple and should be tried. It could probably be combined with method 2 if the compensating system were run on the first harmonic.

General Remarks

Method 2 seems to be the simplest and cleanest way of providing for space charge compensation. But even with such a system in operation, one may not run it in the fashion indicated. What the system does in general is to provide two more variables that are needed for compensation. There may be better ways of choosing these variables than the ones indicated. In particular, it may be possible to use the RF system now planned for the CPS improvement programme both for the additional acceleration and for the required space charge compensation. This should be studied further.

The methods as presented seem alright for cases $\eta < 1$. However, already now the CPS has an $\eta$ of the order of unity, and this may increase with increased intensities. For $\eta > 1$ full compensation after transition would require negative RF restoring forces, and further studies are required to see the implications of this and to see whether that can be tolerated for a limited time near transition.

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