DYNAMIC COMPENSATION DURING STACKING OF THE DE-TUNING CAUSED BY SPACE CHARGE EFFECTS

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Summary

The incoherent tune-shifts, due to space charge, distort the tune values across the machine aperture (working line) and lead to the eventual onset of coherent instabilities. Until recently, for high intensity stacks in the CERN Intersecting Storage Rings (ISR), pre-stressed working lines have been used, which assume an ideal form under a given space charge load. Such lines require a lot of space in the tune diagram making it necessary to tolerate 5th order non-linear resonances inside the stack with a subsequent increase in decay rate and background. By correcting the incoherent tune-shifts during stacking by means of a progressive variation of the currents in the poleface windings, the line never deviates far from its ideal shape. In this way, practically the full tune-spread can be maintained throughout and the line requires less space in the tune diagram. This enables stacks occupying the full width of the vacuum chamber to be kept free of all resonances lower than the 8th order. The corrections are calculated according to the wanted stack position and intensity, so giving a high degree of flexibility. Working line measurements made inside the stack at each step have shown the calculation method to be very accurate. Despite the greater complexity, several variants have been made operational and the highest luminosity, which has been achieved under physics conditions (6.6×10^{30} $cm^{-2}s^{-1}$), has been obtained using this technique in conjunction with stabilization by transverse feed-back on the stacks.

Introduction

The distribution of the horizontal and vertical tunes (Q_H, Q_V) across the machine aperture (working line) is of extreme importance for ISR operation and for physics conditions. Working lines can be conveniently classed as static or dynamic. The former are either made with a disregard for the space charge deformations, e.g. "FP" in Figure 1, or with a pre-stress that gives the line an ideal shape for a given space charge load, e.g. "5C" in Figure 1. These two lines have been extensively used for ISR operation and "FP" is still the principal low intensity line. The philosophy of dynamic lines is to progressively correct the space charge deformations during the stacking so that the working line never departs very far from its ideal form. Operationally this is far more complicated and is only made possible by the very considerable flexibility of the poleface windings under computer control, but the results are amply rewarding.

The Advantage of a Dynamic Line over a Pre-stressed Static Line

Pre-stressed static lines require a lot of space in the tune diagram. This arises because the overall tune-spread has to be large enough to ensure that the local values inside the stack are sufficient for stabilization by Landau damping and secondly because the whole line sweeps across the tune diagram. For these reasons it was not possible to avoid the 5th order non-linear resonances which cross the stacking region on the "5C" line in Figure 1. These particular resonances exhibit a somewhat variable excitation and can cause decay rates of up to 200 parts per million per minute with the background so high as to make physics experiments very difficult if not impossible. In contrast, a dynamically compensated line can be much shorter, since the local tune-spreads inside the stack are maintained close to the maximum value and the line's excursions are very limited. Using the dynamically compensated line "8C", shown in Figure 2, full-aperture stacks of 17.6 A at 26 GeV/c can be made in the region between the 5th and 3rd order resonances, which is free of all resonances up to the 8th order. Compared to "5C", this line is shortened by a factor of 1.5 and the avoidance of the resonances lower than 8th order reliably gives excellent physics conditions.

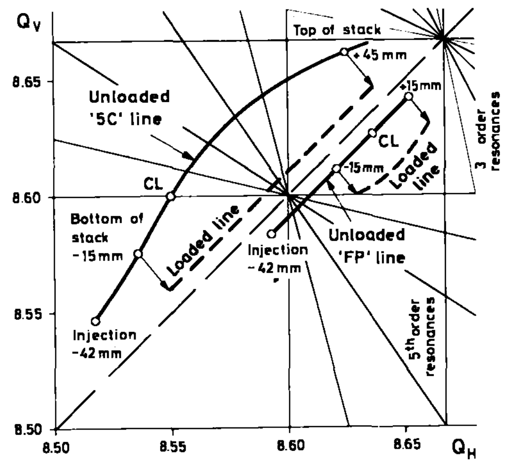

Figure 1. The Static Working Lines "5C" and "FP" shown with and without a Stack.

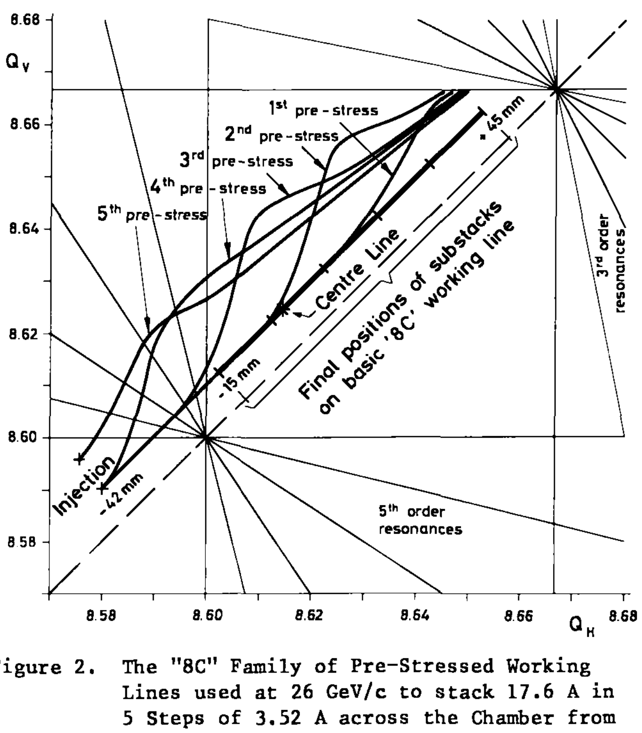

Figure 2. The "8C" Family of Pre-Stressed Working Lines used at 26 GeV/c to stack 17.6 A in 5 Steps of 3.52 A across the Chamber from +45 mm to -15 mm (α_p average).

Calculation of the "8C" Working Line

Equations 1 and 2 are an empirical fit to experimental data obtained in the ISR for the de-tuning caused by space charge. The equipment for measuring these incoherent tune shifts[1] has only recently become fully operational and so extensive measurements have not been made and no measurements yet exist outside the stack. Equations 1 and 2 fit the model shown in Figure 3.

$$\Delta Q_{H,incoh.} = \frac{0.04\ I}{\gamma}\left[1 - \frac{0.8}{L^2}(r-a)^2\right] \qquad (1)$$

$$\Delta Q_{V,incoh.} = \frac{-0.05\ I}{\gamma}\left[1 - \frac{0.8}{L^2}(r-a)^2\right] \qquad (2)$$

where:

$\Delta Q_{H,incoh.}$ and $\Delta Q_{V,incoh.}$ are the incoherent tune-shifts

I is the beam current in ampere

γ is the total energy normalized by the rest energy

a, L, r are geometrical parameters defined in Figure 3.

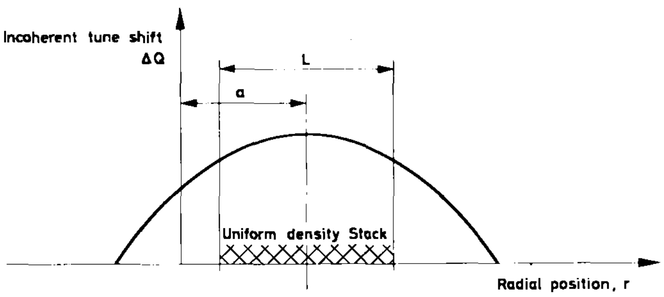

Figure 3. Space Charge Model for the Incoherent Tune-Shift.

Inside the stack these simple expressions work exceedingly well. Outside the stack they probably drop too rapidly to zero, but this is of less importance, except possibly for the injection optimization which depends upon stable conditions.

The necessary working line corrections are calculated by applying equations 1 and 2 to the complete stack after each substack is added. The difference between the overall corrections at each stage gives the pre-stress required for that substack. The pre-stresses are then expressed as an expansion of the tune derivatives with respect to the momentum deviation up to the octupole term. This is done independently for the inner and outer halves of the aperture. Finally, the coefficients are given to the ISR control computer which changes the poleface winding currents accordingly. A short computer program has been written to perform these calculations for any number, size and positions of the substacks.

Practical Realization
of a Dynamically Compensated Line

The base line is first created and recorded in a file specifying all the relevant power supply currents. Re-alignments of the ISR and other changes make it necessary to periodically update this basic file. The pre-stresses, however, need no updating as they are in the form of small changes of tune derivatives, referred to the base line and are, therefore, invarient. Initially, the pre-stresses are checked by measuring the tune values on line[1] after each substack and making any corrections which are necessary. In the case of the "8C" working line (see Figure 2), some small changes in the sextupolar and octupolar terms were needed but the calculated values proved surprisingly accurate. When applying the pre-stresses, the ISR control computer changes all the power supplies in ratio so that the circulating beam sees a smooth transformation which takes only a few seconds. The stack does not show any sign of disturbance. The "8C" stack is built up in 5 steps. Prior to each step the line is pre-stressed (see Fig.2) and then the space charge is added bringing the line back to its ideal form. This procedure is controlled interactively by the ISR computer and it takes about one hour to fill both rings at 26 GeV/c to the maximum current of 17.6 A. At no time does the "8C" working line wander outside the limits shown and the stack always maintains a respectful distance from the diagonal, ($Q_H = Q_V$), the 3rd order resonances and the 5th order resonances. If the full space charge pre-stress were applied in a single step, the stack would be swept across the 3rd and 5th order resonances and would be blown-up and partially destroyed. The "8C" line when loaded to its limit, is sufficiently stabilized by Landau damping to survive under very quiet conditions, but the slightest disturbance will cause the stack to be lost. The active transverse feed-back system is, therefore, used to ensure the stack's stability[2].

Operational Limits and Tolerances for "8C"

The space available for the "8C" line is very limited. It has been found prudent not to allow the tune-separation, $\Delta = Q_H - Q_V$, to fall below 0.01. For example, at $\Delta = 0.005$ the betatron coupling strongly perturbs the tune values and an appreciable percentage (~17 %) of the larger horizontal emittance is coupled into the vertical emittance. Once the tune-separation for the baseline is fixed, the size of a substack and the top and bottom of the main stack are fixed by the space between the base line and the 3rd and 5th order resonances. The tolerances aimed for on the positioning of these lines is ± 0.001. Working lines above the diagonal ($Q_H = Q_V$) have to be pre-stressed prior to loading, whereas the converse is true for lines below the diagonal. Thus, working above the diagonal minimizes the number of power supply changes made with the circulating beam. There is a region on the third pre-stress for the "8C" line (see Figure 2) where the horizontal tune-spread drops locally to virtually zero. This point and other similar points lie outside the stack. Only single pulses cross these regions and their stability has given no problems. The horizontal tune-spread is in any case less important than the vertical one. In order to maintain the tight tolerances on the stack's position in the tune-diagram, the current density has to be carefully controlled to give the correct space charge loading. The radial positions of the substacks are maintained to ± 1 mm to avoid the resonances. To prevent rounding errors accumulating, the maximum number of substacks is limited to eight.

Operational Flexibility with "8C"

At first sight, the "8C" line is rigidly defined and the standard recipe always has to be followed. This is only partially true. As can be seen from equations 1 and 2, the incoherent tune-shifts scale directly with the current and inversely with the normalized energy. With just a few hours for making test stacks, the basic

"8C" scheme can be converted to any energy and to different current densities. Even more simply, substacks and their corresponding pre-stresses can be omitted. Table 1 gives the basic range covered by the "8C" family. There is no intrinsic reason to terminate Table 1 at 3 substacks, except that the intensities given by 1 or 2 substacks are more usually stacked on the "FP" line (see Figure 1). The currents for 5 substacks represent about the operational limit for "8C". Some tests with a six substack variant of "8C", which was designed to support 18 A at 22 GeV/c, revealed a limit at 16 A where transverse instabilities caused the stack to be lost in spite of the active feedback system.

Table 1

Some Variants of the "8C" Working Line

Momentum (GeV/c)	11.780	15.376	22.505	26.588
Linear Current Density (A/mm)	0.14	0.17	0.25	0.29
Substack Combinations				
1 + 2 + 3 + 4 + 5	8.1 A	10.4 A	15.0 A	17.6 A
1 + 2 + 3 + 4	6.5 A	8.3 A	12.0 A	14.1 A
2 + 3 + 4	4.9 A	6.2 A	9.0 A	10.6 A

With such tightly specified lines as "8C", an operational problem arises from unexpected current losses or losses due to scraping. These losses upset the space charge loading on the line and can move it onto the resonances and any further loss on say the 3rd order non-linear resonances only accelerates the working line drift. However, in practice these stacks have extremely low decay rates and rarely require any scraping to improve physics conditions. It has also become increasingly normal practice to correct working line shifts during physics runs. This has been made possible by a method for measuring tunes based on the Schottky noise from the stack[3].

Operational Results

At 22 and 26 GeV/c, "8C" has been extensively used with the full 5 substacks. Typically, the starting luminosities were 5×10^{30} cm^{-2}s^{-1}. More recently, "8C" has been used at 26 GeV/c with the top and bottom substacks omitted giving 10.6 A and with the base line moved further from the diagonal ($Q_H = Q_V$) (see Fig. 4). The most recent of these runs had a starting luminosity of 3.8×10^{30} cm^{-2}s^{-1} with a beam decay rate of 0.8×10^{-6} min^{-1}. During this 27-hour run, the luminosity fell to 2.7×10^{30} cm^{-2}s^{-1} and the decay rate rose to 1.1×10^{-6} min^{-1}. Approximately 40 % of the decay rate can be attributed to beam-beam interactions and the remainder to scattering on the residual gas. Although it is not a proven fact, it appears that the increased tune-separation improves injection optimization and the quality of the stacks. The maximum luminosity so far achieved in the ISR under physics conditions, 6.6×10^{30} cm^{-2}s^{-1}, has also been obtained on the "8C" line.

Future Developments

Incoherent tune measurements outside the stack will help to predict the tune changes at injection. The stability of the injection optimization could then be improved, although there is still the problem of closed orbit shifts due to coherent tune changes.

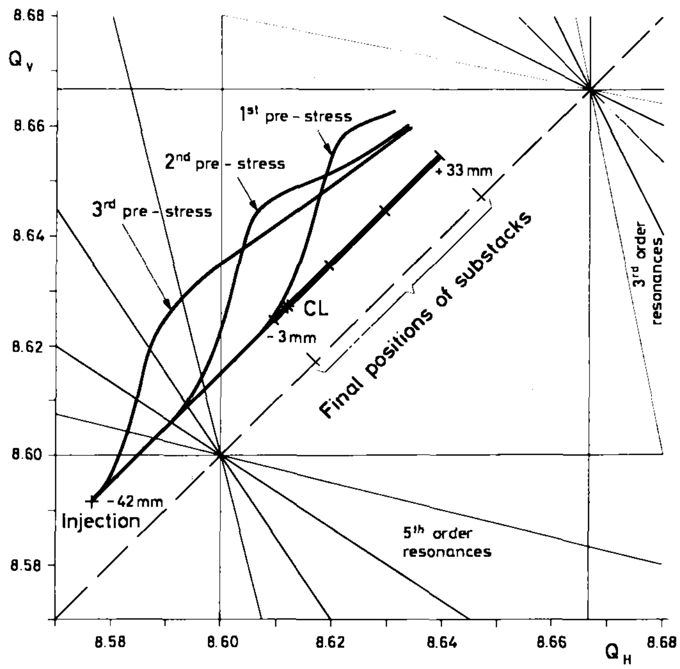

Figure 4. The "8C" Working Lines with the Top and Bottom Substacks omitted to give the Reduced Current of 10.6 A at 26 GeV/c and the Base Line moved away from the Diagonal to give $Q_H - Q_V = 0.015$

In order to stack still higher currents, an increased tune-spread is required. At present, an expanded "8C" line is being developed which extends across the the 5th order non-linear resonances. At the crossing point, the tune-spread is locally increased so that the resonances are traversed more quickly in momentum space. By making separate stacks either side of the 5th order resonances, it is hoped that higher intensities can be reached.

Acknowledgements

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