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THEORETICAL AND OBSERVED BEHAVIOUR OF THE DARESBURY SRS RF SYSTEM

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Abstract

Theoretical predictions of both the steady-state and transient behaviour of the SRS r.f. system are presented. These are compared with observed behaviour which includes anomalous steady-state beam loading and phase oscillations of the beam. The steady-state theory is shown to provide an adequate explanation of observations and some conclusions are drawn about beam phase oscillations.

Introduction

As the r.f. system for the SRS has been progressively improved in service it has become obvious that there are three main phenomena which cause operational difficulties. One of these, higher order resonances in the feeder waveguide, is dealt with in another paper presented to this conference[1]. The other two will be described here. They are:

Anomalous or Differential Cavity Beam Loading

Beam Phase Oscillations.

It will be shown that a rigorous analysis of the steady state operation of the klystron-feeder-cavity-beam system predicts the beam loading phenomena almost exactly. An analysis of the transient behaviour of the beam cavity system will not adequately predict the beam phase oscillations and it is therefore suggested that an adequate theory must include phenomena occurring elsewhere in the storage ring.

Steady State Analysis of the RF System

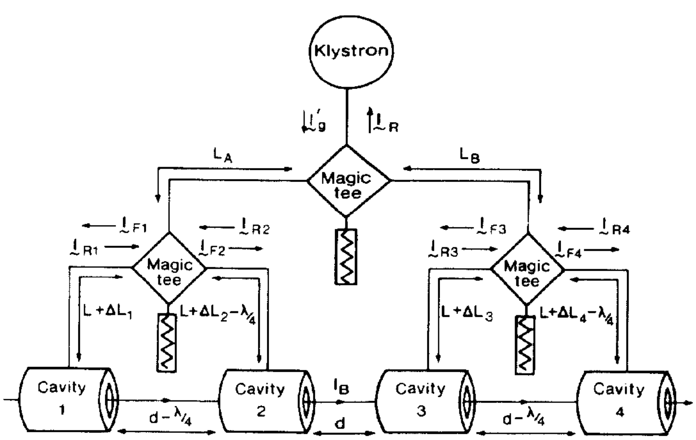


Figure 1. Functional layout of the r.f. system

A functional layout of the r.f. system is shown in Fig.1. The lengths of the various arms can be adjusted by phase shifters and the principle of the circuit design was that by minimising the reflection at the klystron for cavities in a like state of mis-match, some isolation between cavities and klystron would be obtained and also that accurate phasing of the cavities would be ensured. A necessary corollary of this is that the individual cavity tune states must be kept constant and for this purpose a cavity tuning servo accurate to better than ±1/2° in cavity phase was developed.

When the SRS was commissioned it immediately became apparent that the performance of the r.f. system with substantial circulating beams was not as expected. In particular the cavity tuning servo appeared to be inaccurate and would unpredictably fail at low energies. Also beam loading was apparently randomly distributed amongst the four cavities and quite often one or more cavities appeared to have anomalous or reverse beam loading. An example of this is given by the behaviour of the cavity input impedance as a beam is stacked shown in Fig.3(b). Here it can be seen that cavity 4, as the beam increases towards 200 mA, suffers a reduction in impedance by about a factor of 4. The other three cavities conversely appear to increase in impedance. The expected variation for in phase cavities is a reduction of about 10% in impedance as shown in Fig.3(c). The name "differential beam loading" was coined to describe the observations and the term "anomalous" was used for the case when the impedance increased. The observed phenomena were of course complicated by higher order mode effects[1] in the feeder waveguide and by the beam phase oscillations to be described in the second part of this paper.

Initially many of the problems were ascribed to technical faults in newly commissioned equipment and some faults were found and rectified. However when the equipment was demonstrated to be in perfect working order differential beam loading and unpredictable cavity detuning was still experienced. It was also noticed that the phase of the forward power arriving at any particular cavity varied with the state of cavity tuning. Empirical adjustments succeeded in nullifying the differential beam loading but the settings thus found did not minimise power reflection back to the klystron exactly.

The explanation of the phenomena can be found by examining the operation of the r.f. system in detail with regard to small errors in adjustment and the effect of component tolerances. Consider first just the effect of mis-adjustment. Then with reference to Fig.1:

L is nominally equal to an integral number of guide wave lengths. L_A is nominally equal to L_B and to $n\lambda$ and any errors can be transferred to the appropriate ΔL_n, d is an integral number of free space wavelengths.

Then:

The forward current from the klystron is

$$I'_g = I_g + \Gamma_K \cdot I_R$$

where I_g is the primary klystron output and

$$\Gamma_K = \frac{2\beta_K}{1 + \beta_K + j\tan\left[\mathrm{Arg}(I_R) - \mathrm{Arg}(I_g)\right]}$$

is the reflection coefficient of the klystron, β_K is the coupling factor of the klystron to the waveguide.

$$I_{F1} = 1/2\ I_g\ e^{j\Delta L_1}$$

$$I_{F2} = -\ 1/2\ I_g\ e^{j\Delta L_2}$$

$$\underset{\sim}{I}_{F3} = 1/2\ \underset{\sim}{I}_g\ e^{j\Delta L_3}$$

$$\underset{\sim}{I}_{F4} = -\ 1/2\ \underset{\sim}{I}_g\ e^{j\Delta L_4}$$

$$\underset{\sim}{I}_{R_n} = \frac{2\beta'_n}{1 + \beta'_n + j\tan\phi_n}\ \underset{\sim}{I}_{F_n} \qquad n = 1,2,3,4$$

$$\beta' = \frac{\beta_n}{1 + \dfrac{P_{bn}}{P_{cn}}} \qquad n = 1,2,3,4$$

where β_n is the coupling factor of cavity n to its feeder.

ϕ_n is the angular detuning of cavity *n* in the absence of beam. The cavity auto-tuning keeps its effective value constant under beam loading.

The cavity voltage is $\underset{\sim}{V}_{cn}$

$P_{cn} = |\underset{\sim}{V}_{cn}|^2/Z_{cn}$ is the power dissipated in cavity n

$P_{bn} = |\underset{\sim}{V}_{cn}| \cdot |\underset{\sim}{I}_B| \sin\phi_{sn}$ is the power transferred to the beam by cavity *n*

$\underset{\sim}{I}_B$ is the beam current

The total accelerating voltage is

$$\underset{\sim}{V}_c = \sum_{n=1}^{4} \underset{\sim}{V}_{cn}$$

and $$|\underset{\sim}{V}_c| \cdot |\underset{\sim}{I}_b| \sin\phi_s = V_R \cdot |\underset{\sim}{I}_B|$$

ϕ_s is the accelerating phase angle and V_R the radiation loss/turn.

$$\underset{\sim}{V}_{cn} = \frac{(\underset{\sim}{I}_g + \underset{\sim}{I}_{cn})}{Z_{cn}(1 + 2j\ Q_n \tan\phi'_n)}$$

$$\underset{\sim}{I}_{cn} = \underset{\sim}{I}_{Fn}\ (1 - \underset{\sim}{\Gamma}_{cn})$$

These equations form a consistent simultaneous set which can, in principle, be solved analytically. In practice such solutions are complicated and difficult to interpret. Moreover imperfections in the waveguide components of the feeder system induce standing waves in the cavity arms whose contributions to the behaviour of the system are effective errors in the amplitudes and phases of the inputs to the cavities which can be equal in significance to the effects of misadjustment. For these reasons the total system has been analysed numerically.

The basic principle of operation is however fairly obvious. If the cavity fields are not at the same phase with respect to the beam then there will be different beam induced fields in each cavity leading to unbalanced "reflected" power. The unbalanced powers will react with the klystron and with circuit imperfections to further modify cavity fields. The beam itself will take up a phase angle with respect to the vector sum of the net cavity fields which will give it the required energy gain per turn. At the same time the cavity automatic tuning systems are altering the cavity tuners in an attempt to maintain a constant phase between the cavity fields and local monitoring points in the individual cavity feeders. If, in the equilibrium state, the individual cavity phase errors are significant compared to the mean accelerating phase angle then the variation in the vector sums of generator and beam induced fields in individual cavities will be sufficiently large to display differential beam loading.

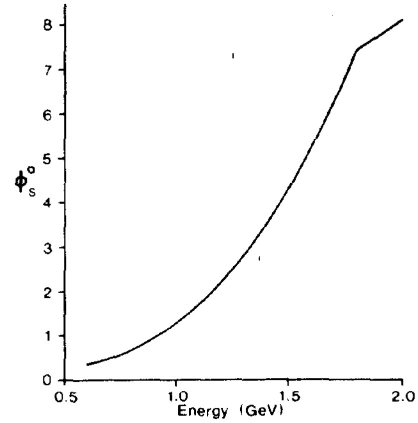
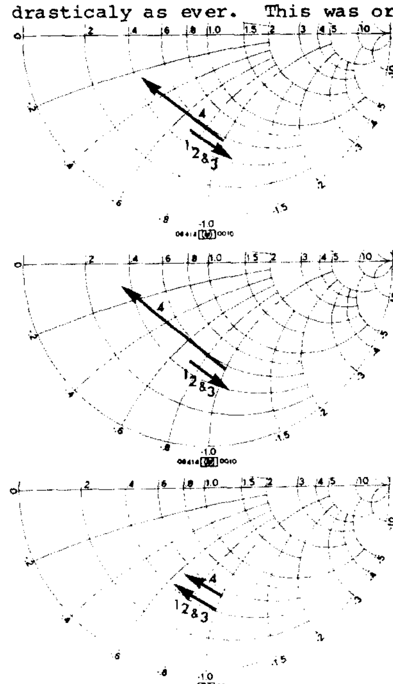


Figure 2. Nominal variation of ϕ_s with energy.

The nominal variation in the accelerating phase angle ϕ_s is shown in Fig.2. The very small value of ϕ_s at the injection energy, 600 MeV, and at lower intermediate energies is because of the need to avoid synchrotron-betatron resonances during acceleration. On the other hand measured circuit imperfections are sufficiently large that tuning the system in the absence of beam could leave residual cavity phase errors of the order of 5°. Thus one would expect differential beam loading to be a significant problem up to energies well above 1.5 GeV and this was in fact operational experience. Obviously empirical correction of differential beam loading was attempted while the investigation of the phenomena was in progress. It appeared quite easy to do this for a given beam current and energy but as soon as there was a significant change in either then the phenomena would reappear as drasticaly as ever. This was originally attributed to



(a) Calculated with cavity 4 detuned by 5°.

(b) Observed with cavity 4 detuned by 5°.

(c) Observed with all cavities tuned.

Figure 3. Cavity input impedance variation as beam current increases.

errors developing in the automatic tuning systems due either to differing generator power levels or to beam induced higher order modes in the cavities. However analysis shows quite clearly that it is possible to mis-adjust the system so that at a fixed beam energy and current there appears to be no differential beam loading but that this balance is destroyed by any change.

A comparison between theory and obsevation is provided by Figs.3(a) and (b). Figure 3(a) shows the predicted variation in cavity input impedance for the situation in which cavities 1 to 3 have equal detuning but cavity 4 is detuned 5° less. The loci of impedance shown correspond to the beam current increasing from zero to 200 mA. Figure 3(b) shows the observed variation with the same conditions. The agreement between theory and practice is well within experimental error. Figure 3(c) shows the behaviour when all the cavities are properly phased together.

Transient Behaviour of the RF System

The beam in the SRS performs an unexpected low frequency phase oscillation. The amplitude of the oscillation is directly proportional to the circulating beam current and inversely proportional to the square of the cavity voltage. The period of the oscillation varies to a small extent, but this variation cannot be correlated to any machine parameter setting.

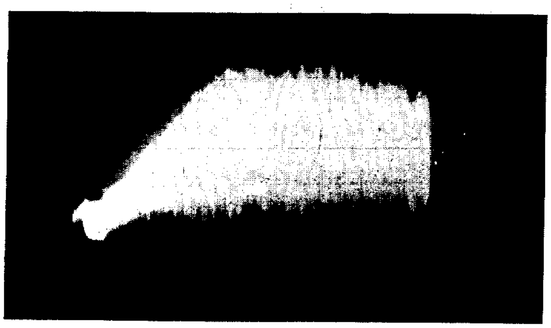


Figure 4. Incidence of phase oscillations as beam accumulates.

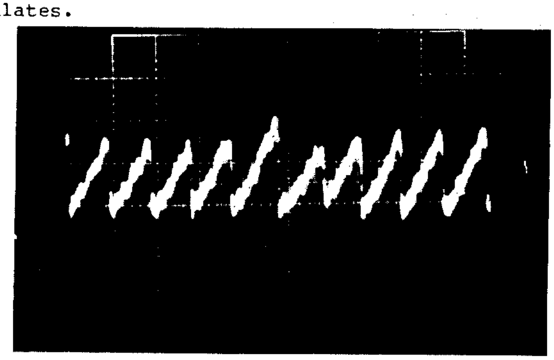


Figure 5. Details of phase oscillations. Scale 10° and 10 mS/division.

The observed incidence of the oscillation as beam accumulates is shown in Fig.4 and the detailed typical phase variation is shown in Fig.5. It is monopolar and has the classic sawtooth characteristic of a relaxation oscillation. Apart from cavity voltage and beam current, the only parameters which effect the amplitude of the oscillation are the settings of the variable phase shifters in the feeder waveguide. The incidence of the oscillation is not affected by the number of cavities in use nor by any of the feedback systems on the r.f. system when working normally.

The oscillation makes accurate setting of the cavities very difficult and when the amplitude is large can even result in Robinson instability at injection. This effect is one of the limits on the current which can be accumulated and so the oscillation must be suppressed if possible.

There has been much experimental investigation of the oscillations. No link has been established between them and higher order modes in the cavities or electromagnetic modes induced in the rest of the machine. The presumption must therefore be that they are caused by the r.f. system. Since the oscillation is manifest with only one cavity in use, detailed analysis will be restricted to that case.

The transient response of a single cavity with a circulating beam can be written[2]

$$\begin{pmatrix} \Delta V_c \\ V_c\,\Delta\phi_{Vc}\end{pmatrix} = \frac{\left[\dfrac{R\alpha}{(s+\alpha)^2+\alpha^2\tan^2\psi}\begin{pmatrix} s+\alpha & \alpha\tan\psi \\ -\alpha\tan\psi & s+\alpha\end{pmatrix}\begin{pmatrix}\Delta I_g \\ I_g\,\Delta\phi_{Ig}\end{pmatrix}\right]}{\left[1+\dfrac{I_g R\alpha\,\Omega_s^2}{V_c\cos\phi_s(s^2+\Omega_s^2)\left[(s+\alpha)^2+\alpha^2\tan^2\psi\right]}\right]}$$

$$(s^2+\Omega_s^2)\Delta\phi_s = \frac{\Omega_s^2}{V_c\cos\phi_s}\left(-\sin\phi_s \quad \cos\phi_s\right)\begin{pmatrix}\Delta V_c\\ V_c\,\Delta\phi_{Vc}\end{pmatrix}$$

where: V_c, ϕ_{Vc} are the amplitude and phase of the cavity voltage
I_g, ϕ_{Ig} are the amplitude and phase of the generator current
α is the cavity time constant
ψ is the cavity detuning angle
R is the cavity shunt impedance
Ω_s is the synchrotron oscillation frequency
ϕ_s is the beam phase
s is the Laplace operator

The transient response has been analysed numerically with the following results:

(a) Other than the usual synchrotron oscillation there is no self-sustaining oscillation of beam phase

(b) Modulation of the generator current with time constants significantly less than that of the synchrotron oscillation produces an approximately similar variation in beam phase.

It would therefore seem that the most likely cause of the phenomenon is to be found in the klystron. Investigation has revealed that there are variations in the klystron output which appear to correlate to the beam phase oscillations. Presumably the inducement is the variation in cavity input impedance due to beam loading. Why the oscillations take the form of relaxation oscillations is not known.

In the near future it is proposed to fit ferrite isolators between klystron and cavities. Hopefully this will suppress these beam phase oscillations.

References

1. D.M. Dykes, A. Jackson and B. Taylor, Breakdown and Resonance Behaviour of the SRS Waveguide. Paper presented at this Conference.

2. M.H.R. Donald, E.A. Hughes and D.J. Thompson, R.F. Cavity Voltage Stabilising System. Daresbury Laboratory Internal Report EL/TM/37 (1966).