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A DOUBLE FREQUENCY R.F. SYSTEM TO INCREASE THE D.C.I. ENERGY†

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Summary

The D.C.I. RF system was designed for a maximum energy of about 1.8 GeV. In order to reach the ψ' resonance at 1.85 GeV the system has to be improved knowing that the magnet limitation is 1.9 GeV. The available space around the ring just permits to add up a second cavity with a frequency four times higher than the present RF frequency. The design of such a double frequency RF system is described and the expected behaviour discussed.

Introduction

The present RF limitation is due to the maximum accelerating voltage one can get in the 17 cm cavity gap with 2.7 MΩ shunt impedance. Due to the lack of free space around the ring it was not possible to add a second cavity identical to the present one, at 25 MHz. However, a straight section one meter long is still available where a smaller cavity can be installed (⩾ 100 MHz). Then the idea is to use as much as possible the main cavity voltage (which means that the synchronous phase can reach the maximum value of 90° to compensate for beam power loss at high energy[1]. With these conditions the region for stable phase oscillations is reduced to zero. The additionnal cavity then, is supposed to provide the necessary slope for stable phase oscillations and good quantum lifetime. This is obtained by a suitable phase difference between the RF signal in the two cavities so that the synchronous phase of the auxiliary cavity remains zero (Fig. 1). This second cavity does not supply any power to the beam and thus the cavity can be fed with a low power transmitter.

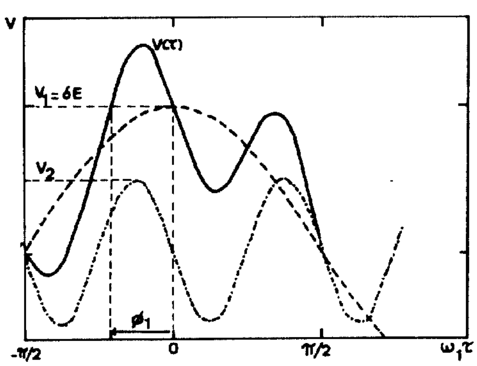

Fig. 1 : Phasing of the two cavities

Such an additionnal RF has been designed for one of the D.C.I. rings and is now under construction. The reason to limit the modification to one ring only is suggested by the following facts :

a) Such a system has never been used on a storage ring so we don't know exactly if it will be easy enough to operate.

b) At high energy the maximum currents will be limited by RF power when using the space charge compensation scheme. Then, the gain in using four beams at high energy may not be large enough to justify the complexity of the new routine.

Design of the auxiliary RF

The auxiliary RF is designed to raise the maximum energy of D.C.I. to 1.9 GeV, which is the limit corresponding to magnet saturation and power supplies. The frequency has been choosen to be 101.41 MHz. In what follows index 1 will refer to the main RF, index 2 to the auxiliary RF.

At 1.9 GeV the characteristics of D.C.I. are :

Loss per turn : $\delta E = 365.6$ kVolts
Synchrotron damping : $\tau_s = 1.57$ ms
Energy dispersion : $\frac{\sigma_E}{E} = 8.05\times10^{-4}$

The quantum lifetime is given by :

$$\tau_q = \frac{\tau_s}{2\delta} e^{\delta} \quad \text{with} \quad \delta = \frac{1}{2}\left(\frac{\varepsilon_{RF}}{\sigma_E}\right)^2$$

where ε_{RF} represents the energy acceptance of the double RF system (see ANNEX).

$$\left(\frac{\varepsilon_{RF}}{E}\right)^2 = \frac{eV_1}{\pi g h_1 E}\left\{\frac{1}{4}\frac{V_2}{V_1}(1-\cos 4\phi_1) + (\phi_1 - \sin\phi_1)\right\}$$

where ϕ_1 is solution of the following equation :

$$\frac{\cos\phi_1 - 1}{\sin 4\phi_1} = \frac{V_2}{V_1} \qquad \left(-\frac{\pi}{4} < \phi_1 < 0\right) \qquad V_1 = \delta E$$

which is tabulated on Fig. 2.

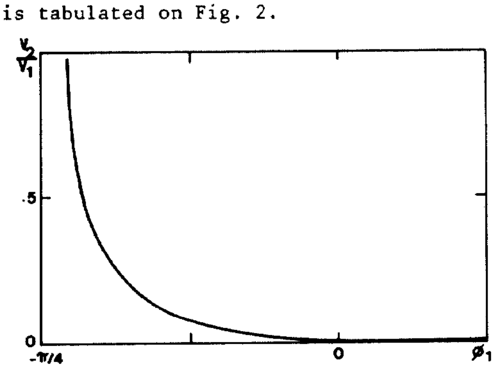

Fig. 2 : Tabulation of the function : $\frac{V_2}{V_1} = \frac{\cos\Phi_1 - 1}{\sin 4\Phi_1}$

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A decent quantum lifetime, let say τ_q = 100 h, is obtained for δ = 23 which means :

$$\left(\frac{\varepsilon_{RF}}{E}\right)^2 = 2.98\times10^{-5} .$$

Fig. 3 gives then $\left(\frac{\varepsilon_{RF}}{E}\right)$ as a function of $\frac{V_2}{V_1}$, ratio

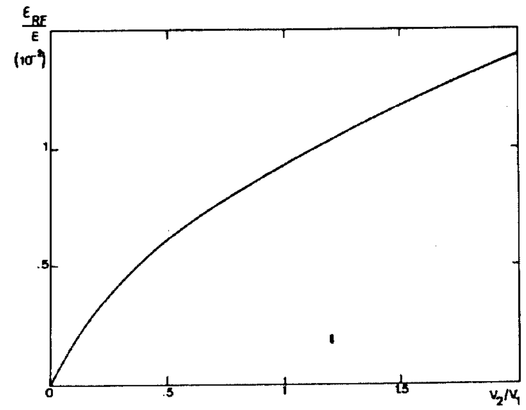

Fig. 3 : Energy acceptance of the double frequency RF system versus the ratio of the voltages. (E = 1.9 GeV ; τ_q = 100 h ; $\bar{g}$ = .04 ; h_2 = 4 h_1 = 32).

between the additionnal RF voltage and the main one. It follows that the minimum required voltage on the auxiliary cavity is :

$$V_2 = 157 \text{ kVolts}$$

A 101.4 MHz reentrant cavity with 12 cm gap has been designed to have a shunt impedance of 3 MΩ which means that the minimum power required to feed the cavity is 4 kW. As said before, the auxiliary cavity does not give power to the beams, so we choose to use a 10 kW transmitter which gives a correct amount of security factor for the power. Let remind that the main transmitter provides 350 kW.

Stability of the "Beam-Double RF" System

With an usual RF system, the stability of the beam-RF interaction is given by the Robinson criterion[2] :

$$0 < \sin 2\,\phi_y < 2\,\frac{V}{V_f}\cos\phi_s$$

where ϕ_y represents the cavity detuning angle, ϕ_s the synchronous phase, V_f the beam induced voltage, V the total voltage in the gap. For a matched system :

$$\operatorname{tg}\phi_y = \frac{V_f}{V}\cos\phi_s$$

The left side of the inequality is generally satisfied as soon as partial or total beam reactance compensation is done. The main feature then corresponds to the right side of the inequality and the limit is connected to the intensity of the stored current. The stability condition can be written in the following way[3,4,5] :

$$P_f \leqslant \frac{V^2}{2R} \quad \text{(compensated case)}$$

where P_f is the power delivered to the beam, and R the loaded shunt impedance.

For D.C.I., which is a high impedance system, R is practically equal to the cavity shunt impedance R_s which means that we are not in the matched conditions described by ROBINSON, and the limit becomes an important concern.

In the special case of a double frequency RF system as described above, the ROBINSON criterion can be extended[4,5], and written in the following way :

$$V_1\cos\phi_{s1} - \frac{1}{2}V_{f1}\sin 2\phi_{y1} + 4\,V_2 - 2\,V_{f2}\sin 2\phi_{y2} \geqslant 0$$

with in addition for the compensated case :

$$\operatorname{tg}\phi_{y1} = (V_{f1}/V_1)\cos\phi_{s1}$$

$$\operatorname{tg}\phi_{y2} = V_{f2}/V_2 \qquad (\phi_{s2} = 0°)$$

Detailed study of that inequality leads to the following conclusions :

a) Perfect operating conditions, ϕ_{s1} = 90° ϕ_{s2} = 0°, and compensation for beam reactance lead to absolute stability even for an unmatched system like the D.C.I.

b) Tolerances on ϕ_{s1} are very stringent unless ϕ_{s1} is choosen higher than 90° ; but in that condition ϕ_{y1} must be negative for the compensated case which will require a feedback system anyway to control for dipole phase oscillations.

c) Tolerances on the operating parameters of the auxiliary cavity do not appear to be difficult to meet.

Double Frequency RF System Operations

The system described above needs specific feedback loops in addition to the usual ones which are necessary for each cavity (tuner, phase, amplitude).

Two main functions have to be solved :

1) The synchronous phase ϕ_{s2} must be zero within good tolerances (< 1°) in order to avoid power going to the beams, or coming from the beams.

The adopted solution as shown on Fig. 4 consists of comparing the input voltage of the transmitter to the cavity voltage.

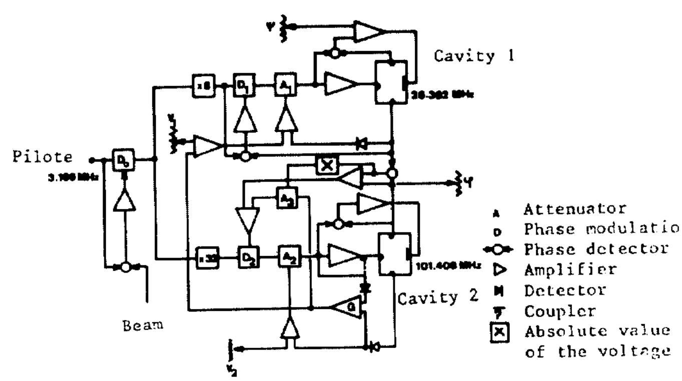

Fig. 4 : Servo-loops for the double RF system.

The transmitter has been designed to have a good linearity over the useful power range. The loop calibration is such that without beam no signal comes out from the voltage comparison. With a stored beam, if $\phi_{s2} \neq 0$, a signal will appear which will drive the main cavity voltage V_1 in order to shift the beam according to the auxiliary voltage V_2 and then give back the right synchronous phase $\phi_{s2} = 0$. A second loop with less priority but more sensitivity will also act on the phase of the auxiliary cavity.

2) The phase difference between the voltages in both cavities must be adjusted in order to have, in the normal operation mode : $\phi_{s1} = 90° + \varepsilon$, $\phi_{s2} = 0°$. This is obtained with the potentiometer Φ (see Fig. 4). According to the fact that ϕ_{s2} is maintained equal to zero, this will determine ϕ_{s1} by adjusting V_1. The phase detector gives zero output for $\phi_{s1} = 90°$ and in that case the attenuation from A3 is maximum to avoid phase ambiguity at $\phi_{s1} \simeq 90°$.

Howewer in the normal operation mode we may lose on the injection rate with shorter buckets unless we are able to reduce the Linac pulse without losing too much peak current. Otherwise we will inject with the main cavity alone (V_2 low enough not to perturbe the main bucket) and after injection the auxiliary voltage will be increased and the bucket will be compressed. Then, for instance the path toward $\phi_{s1} = 90°$ will be automatically done when ramping the energy up to its maximum value. But it is shown theoretically[5] that the beam-cavities interaction will become a serious problem when ϕ_{s1} will approach 90° and that it is impossible to reach 90° with high currents. Notice that at high current the stability effect of the auxiliary cavity becomes so small that the instability threshold is practically given by the main cavity, and for the D.C.I. case it can be written :

$$P_f = P_J$$

or

$$i_{max} = \frac{\delta E}{2R_s \sin^2\phi_{s1}}$$

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Annex

We propose to compute here the energy acceptance of the double frequency RF system in the normal operation mode. The method used was proposed by M. SANDS[6,7].

Let τ be the particle arrival time as compared to the RF voltage in the main cavity. The energy gain per turn as shown on Fig. 1 is :

$$V(\tau) = V_1 \cos \omega_1\tau - V_2 \sin 4\,\omega_1\tau \qquad (V_1 = \delta E)$$

the synchronous particle corresponding to $\tau = 0$.

Let $\omega_1 \tau_1$ be the maximum phase displacement compatible with stable oscillation. Then :

$$V(\tau_1) = V_1 = \delta E$$

and if we write : $\phi_1 = \omega_1 \tau_1$

it comes :

$$\frac{\cos \phi_1 - 1}{\sin 4\,\phi_1} = \frac{V_2}{V_1}$$

the solution of which equation is tabulated on Fig. 2. The equations for the synchrotron motion, with τ as the independant variable, are :

$$\frac{d\tau}{dt} = \bar{g}\,\frac{\varepsilon}{E} \qquad (\bar{g} = \text{momentum compaction})$$

$$\frac{d^2\tau}{dt^2} = \frac{\bar{g}\,f_r}{E}\left\{eV(\tau) - eV_1\right\}$$

where the bracket represents the energy gain per turn, and ε is the energy deviation.

The potential associated to the system is :

$$\Phi(\tau) = -\frac{\bar{g}\,f_r}{E}\int_0^\tau \left\{ eV(\tau) - eV_1 \right\} d\tau$$

and the principle of energy conservation implies :

$$\frac{1}{2}\left(\frac{d\tau}{dt}\right)^2 + \Phi(\tau) = \Phi_o = \text{cte}.$$

For the energy oscillation then one gets :

$$\frac{\varepsilon(\tau)}{E} = \pm\frac{\sqrt{2}}{\bar{g}}\left[\Phi_o - \Phi(\tau)\right]^{1/2}$$

The separatrix is connected to the maximum phase excursion :

$$\Phi_{o\,max} = \Phi(\tau_1)$$

and the energy acceptance is defined as the motion on that separatrix for $\tau = 0$, which means :

$$\frac{\varepsilon_{max}}{E} = \frac{1}{\bar{g}}\left[2\,\Phi(\tau_1)\right]^{1/2}$$

and after integration one gets the following final result :

$$\left(\frac{\varepsilon_{max}}{E}\right)^2 = \frac{eV_1}{\pi h_1 \bar{g} E}\left\{\frac{V_2}{4\,V_1}(1 - \cos 4\,\phi_1) - (\phi_1 - \sin\phi_1)\right\}$$

References

[1] M. Bergher, J.C. Bourdon, P. Brunet, J. Le Duff, NI/24-75 "Anneaux de Collisions", Laboratoire de l'Accélérateur Linéaire, Orsay (1975).

[2] K.W. Robinson, CEAL 1010, Cambridge Electron Accelerator Laboratory (1964).

[3] S. Getka, NI/20-73 "Anneaux de Collisions", Laboratoire de l'Accélérateur Linéaire, Orsay (1973).

[4] J. Le Duff, Stabilité de l'interaction faisceau-RF (notes non publiées).

[5] M. Sands, RT/2-76, RT/3-76, and RT/4-76, "Anneaux de Collisions", Laboratoire de l'Accélérateur Linéaire, Orsay (1976)

[6] M. Sands, Private communication.

[7] M. Sands, SLAC 121, Stanford (1970).