Study of the UNK Accelerating Structure under Beam Loading with Tuning and Coupling Mismatch

V.Katalev
Institute for High Energy Physics
Protvino, Moscow region, 142284, Russia

Abstract

The UNK accelerating structure consists of two non-tuned single-cell 200 MHz cavities linked together by a 3 dB quadrature hybrid. The 850 KW power amplifier is connected to the input port of the hybrid via a long (~40 - 60 m) waveguide. The required accelerating voltage per two cavities is about 1.2 MV, while the fundamental RF harmonic of the proton beam may well achieve 3 A (for 6×10^{14} ppp). The steady regimes of the accelerating structure operation are analyzed under different conditions of beam loading. The mismatch in tuning angle and coupling coefficient, the non-ideal dummy load of the hybrid and the production tolerances result in a voltage standing wave ratio (VSWR) greater than unit as seen in the RF power amplifier port, the frequency variation during the beam acceleration being $\Delta f/f \approx 10^{-4}$. Dependencies of the RF power and phase on beam current are calculated with accelerating voltage phase and amplitude tolerances being taking account.

1 INTRODUCTION

The accelerating system for the UNK first ring consists of 8 identical RF units. Six of them drive accelerating voltage of 7 MV per turn, and two others are intended for reserve and fine adjustment of the accelerating voltage. Synchronous phase angle ϕ_s is about 73° (w.r.t. voltage crest). Dynamics of the longitudinal beam motion requires to keep the accelerating voltage amplitude and phase with accuracy ±5% and ±5°, respectively.

Orbit of the UNK first ring is to be filled in series by 12 trains injected from the existing proton accelerator U-70. The train length is 5μs, and the pause between trains is about 0.6μs. The power delivered to beam by a single unit is about 512 kW while the power losses in two cavity walls is 73 kW. The unloaded cavity quality factor Q_0 is 50 000, the effective shunt impedance R_1 of a single cavity is 4.6 MΩ and the transit time factor is 0.761. All the RF power amplifiers are placed in a serviced surface utility building and are connected to the RF structure with a rectangular waveguide [1]. Allowable value of VSWR at the input port of the hybrid must not exceed 1.3 throughout the whole frequency range. Taking account of tolerances allowed for production and assembling of accelerating structure, the difference in hybrid port to cavity phase lengths may well reach $\phi \approx 5°$. Besides, the dummy load itself can bring about VSWR $\lesssim$ 1.1. All these factors, along with tuning and coupling mismatch of the cavities subject to a heavy pulsed beam loading, would result in an undesirable reflected wave from the hybrid input port.

2 GENERATOR POWER AND CAVITIES TUNING

First, let us consider one of the accelerating cavities. Usually, in the vicinity of the fundamental resonance the cavity is represented by a parallel circuit [2],[3] with its impedance being

$$Z_c = \frac{R_1}{1+j\xi},$$

where $\xi = 2Q_0\Delta f/f_0$ is a reduced cavity detuning, Δf is a shift between accelerating and resonance frequencies, $\Delta f = f - f_0$.

This impedance is shunted by a feeder impedance transformed into the cavity gap, R_1/β, with β being a standard coupling coefficient. We shall consider the interaction of the fundamental components of beam and generator currents with the cavity (a steady state condition). Fig.1 shows the equivalent circuit and the phasor diagram (above transition) with accelerating voltage V_1 taken as a reference.

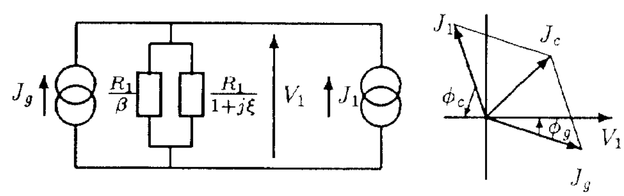

Figure 1: Equivalent circuit and phasor diagram.

The total voltage across cavity gap is a superposition of voltages induced by beam and generator currents,

$$V_1 = (J_g e^{-j\phi_g} - J_1 e^{j\phi_s})\frac{R_1}{1+\beta+j\xi}, \quad (1)$$

where $J_g = \sqrt{4P\beta/R_1}\ e^{-j\phi_g}$ is an equivalent generator current as transformed into the cavity gap.

Eq.1 yields the RF power to drive the required accelerating voltage V per two cavities ($V = 2\cdot V_1$)

$$P = \frac{V^2}{16\beta R_1}\left[(1+\beta+2i\cos\phi_s)^2 + (\xi - 2i\sin\phi_s)^2\right] \quad (2)$$

where $i = J_1 R_1 / V$ is a reduced beam loading parameter (for the UNK first ring, $i_{max} \approx 12$).

It is essential, that accelerating voltage during the train passage through the cavity (beam loading) must be equal to the voltage in pause between trains (no beam loading). In this case amplitudes of phasors J_c and J_g will be coincide (see phasor diagram). Minimizing RF power for the accelerating structure, one gets the optimum cavity tuning,

$$\xi_0 = \frac{(1+\beta)\cos\phi_s + i}{\sin\phi_s} \tag{3}$$

and its coupling

$$\beta_0 = \sqrt{(1 + 2i\cos\phi_s)^2 \sin^2\phi_s + (\cos\phi_s + i\cos 2\phi_s)^2}. \tag{4}$$

Then phase between generator current and cavity voltage would be not equal to zero:

$$\tan\phi_g = \frac{2i\sin\phi_s - \xi}{2i\cos\phi_s + 1 + \beta}. \tag{5}$$

3 TWO CAVITIES DRIVEN BY 3 DB HYBRID

Fig.2 gives a network of two cavities driven by a 3 dB quadrature hybrid. The port-1 phase is behind the port-2 one by 90°. Thus, the beam may be accelerated from cavity-1 to cavity-2 direction only.

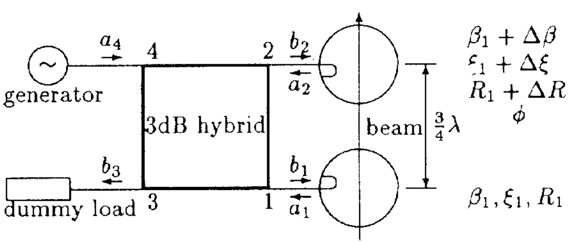

Figure 2: Network of two cavities driven by a 3 dB hybrid.

Let a_k(k=1,2,3,4) be forward waves at the hybrid, b_k be reflected waves, a_k, b_k being normalized as

$$p_{ak} = \frac{a_k a_k^*}{2} = \frac{P_{ak}}{P_o} \tag{6}$$

where $P_o = V^2/4R_1$

$P_{ak} = V_{fk}^2/2Z_k$ - forward power of k-port

V_{fk} - forward voltage of k-port,

Z_k - feeder impedance ,

p_{ak} - dimensionless forward power.

The similar identities hold for the reflected waves.

Relation between forward and reflected waves is a well known one, [4]:

$$[b] = [S] \cdot [a] \tag{7}$$

here $[b]$, $[a]$ are column-matrices of reflected and forward waves, accordingly; $[S]$ is a scattering matrix of the hybrid. Measurements reported in [1] show that the ideal scattering matrix of [4] can be employed to describe the real hybrid. Phase difference ϕ between port-1 and -2 of the hybrid would virtually shift the reference plane of one of the ports (let it be that of port-2). Then Eq.7 gives

$$\begin{aligned} b_1 &= (a_3 - ja_4)/\sqrt{2} \\ b_2 &= (-ja_3 e^{-j\phi} + a_4 e^{-j\phi})/\sqrt{2} \\ b_3 &= (a_1 - ja_2 e^{-j\phi})/\sqrt{2} \\ b_4 &= (-ja_1 + a_2 e^{-j\phi})/\sqrt{2} \end{aligned} \tag{8}$$

Forward waves in ports 1 and 2 are superpositions of two waves: the first one is the generator wave reflected from cavity, and the second one is imposed by beam excitation of the cavity

$$\begin{aligned} a_1 &= \Gamma_1 b_1 + \Delta a_1 \\ a_2 &= \Gamma_2 b_2 + \Delta a_2 \end{aligned} \tag{9}$$

where Δa_1, Δa_2 are normalized waves imposed by beam.

Let coupling, tuning and shunt impedance of the second cavity be different from that of the first one

$$\beta_2 = \beta_1 + \Delta\beta, \quad \xi_2 = \xi_1 + \Delta\xi, \quad R_2 = R_1 + \Delta R.$$

Then Eqs.9 can be rewritten

$$\begin{aligned} \Delta a_1 &= jie^{-j\phi} \cdot \frac{2\sqrt{\beta_1}}{1+\beta_1+j\xi_1} \\ \Delta a_2 &= -ie^{-j\phi} \cdot \frac{2\sqrt{\beta_1+\Delta\beta}\cdot\sqrt{1+\frac{\Delta R}{R_1}}}{1+(\beta_1+\Delta\beta)+j(\xi_1+\Delta\xi)} \end{aligned} \tag{10}$$

Reflection coefficients from cavities at these ports are

$$\Gamma_1 = \frac{\beta_1 - 1 - j\xi_1}{\beta_1 + 1 + j\xi_1}, \qquad \Gamma_2 = \frac{\beta_2 - 1 - j\xi_2}{\beta_2 + 1 + j\xi_2}$$

As the dummy load is a non-ideal one ($\Gamma_3 \neq 0$), one can put down $a_3 = \Gamma_3 \cdot b_3$

On taking account of the restrictions mentioned above, and on solving Eqs.8 w.r.t. reflected waves, one obtains

$$\begin{aligned} b_1 &= -\frac{j}{2F}\left\{\sqrt{2}a_4(1 + \Gamma_2\Gamma_3 e^{-j2\phi}) - ie^{-j\phi}\cdot\Gamma_3(F_1 + F_2 e^{-j\phi})\right\} \\ b_2 &= \frac{e^{-j\phi}}{2F}\left\{\sqrt{2}a_4(1 - \Gamma_1\Gamma_3) + ie^{-j\phi}\cdot\Gamma_3(F_1 + F_2 e^{-j\phi})\right\} \\ b_3 &= -\frac{j}{2F}\left\{a_4(\Gamma_1 + \Gamma_2 e^{-j\phi}) - ie^{-j\phi}\cdot\sqrt{2}(F_1 + F_2 e^{-j\phi})\right\} \\ b_4 &= \frac{1}{2F}\Big\{a_4(-\Gamma_1 + \Gamma_2 e^{-j2\phi} - 2\Gamma_1\Gamma_2\Gamma_3 e^{-j2\phi}) + \\ &\quad + ie^{-j\phi}\cdot\sqrt{2}\left[F_1(1 + \Gamma_2\Gamma_3 e^{-j2\phi}) - F_2(1 - \Gamma_1\Gamma_3)e^{-j\phi}\right]\Big\} \end{aligned} \tag{11}$$

where $F = 1 - \Gamma_3(\Gamma_1 - \Gamma_2 e^{-j2\phi})/2$

$$F_1 = \frac{2\sqrt{\beta_1}}{1+\beta_1+j\xi_1}, \qquad F_2 = \frac{2\sqrt{\beta_1+\Delta\beta}\cdot\sqrt{1+\Delta R/R_1}}{1+(\beta_1+\Delta\beta)+j(\xi_1+\Delta\xi)}$$

$$a_4 = \sqrt{2p}\cdot e^{-j\phi_g}, \qquad p = P/P_0$$

Total voltages across the cavities are superpositions of the forward and reflected waves. Eqs.6,9 result in

$$\begin{aligned} V_1 &= \frac{V}{2\sqrt{\beta_1}}\left[b_1(1 + \Gamma_1) + \Delta a_1\right] \\ V_2 &= \frac{V}{2\sqrt{\beta_1}}\sqrt{\frac{1 + \Delta R/R_1}{1 + \Delta\beta/\beta_1}}\left[b_2(1 + \Gamma_2) + \Delta a_2\right] \end{aligned} \tag{12}$$

VSWR at the input port is

$$\rho_4 = \frac{|b_4/a_4| + 1}{|b_4/a_4| - 1} \tag{13}$$

Eqs.11,12,13 describe the steady regimes of the accelerating structure with beam loading.

4 SOME RESULTS

Frequency variation $\Delta f/f = 10^{-4}$ during the proton beam acceleration corresponds to cavity detuning in range of $\xi = 0 - 10$. Fig.3 shows the required RF power vs. ξ in acceleration regime with maximum current ($i = 0$ in pause between trains, and $i = i_{max}$ during the train passages).

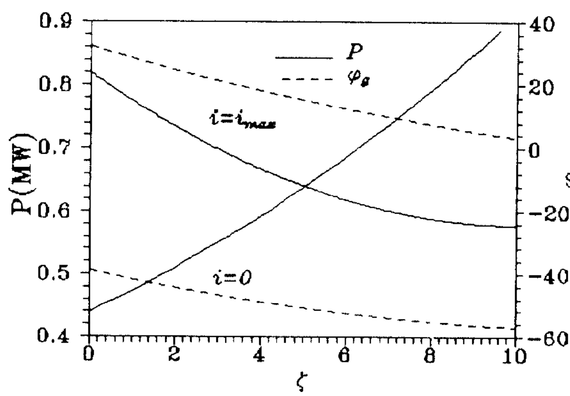

Figure 3: Power and phase of RF generator.

To keep accelerating voltage within the tolerances prescribed, it is necessary to vary RF power P and its phase ϕ_g in accord to beam loading during the whole acceleration cycle. The cavities are coupled and tuned according to Eqs.3,4 at the center of the frequency variation range.

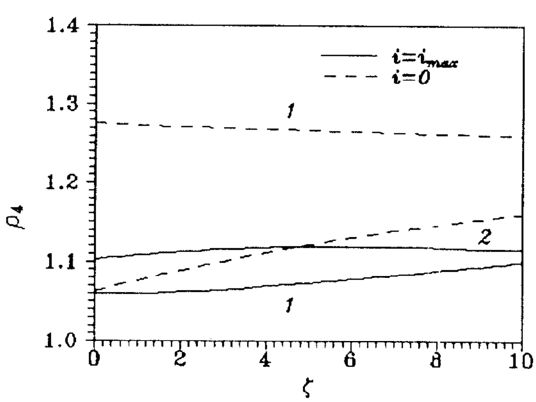

Figure 4: VSWR at the hybrid input port with beam loading ξ_1=16, β_1=12.3, $\Delta\beta$=0.5, ρ_3=1.1, ϕ=5°, ϕ_s=73°. Curves 1: $\Delta\xi = 0.5$, curves 2: $\Delta\xi = -1.7$

Fig.4 shows variation of the input port VSWR for different mismatches in tuning and coupling of cavities. In the whole frequency range ρ_4 with heavy beam loading is less than the ultimate tolerable value of 1.3, even despite the sufficiently large mismatches in tuning and coupling (curves 1). It is even possible to reduce VSWR by detuning the cavities in a different way (curves 2).

The RF structure becomes more sensitive to cavity tuning for a low intensity beam acceleration ($i_{max} \approx 0$), curve 1 of Fig.5. VSWR can be reduced to a tolerable value either by retuning of one of the cavities (curve 2), or by increasing coupling to $\beta_1 = 6.1$ (curve 3). Moreover, in the last case average RF power consumed by accelerating structure is reduced from 0.24 MW to 0.18 MW.

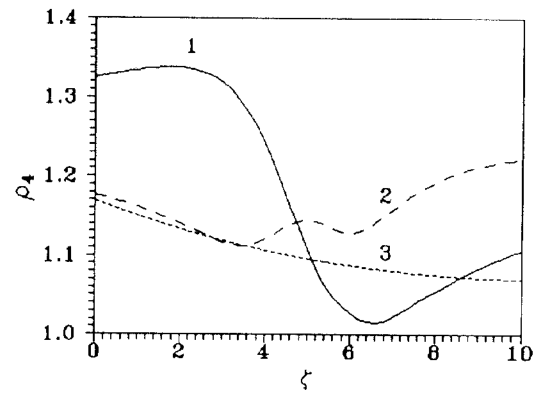

Figure 5: VSWR at the hybrid input port without beam loading ξ_1=0, β_1=1, ρ_3=1.1, ϕ=5°, ϕ_s=73°. Curve 1: $\Delta\xi$=0.2, $\Delta\beta$=0.2, curve 2: $\Delta\xi$=-0.25,$\Delta\beta$=0.2, curve 3: β_1=6.1, $\Delta\xi$=0.2, $\Delta\beta$=0.3

Thus, the accelerating structure assembled of two non-tuned cavities driven by a 3 dB hybrid is not crucially sensitive to the cavity tuning and coupling mismatches, as well as to the tolerances of its production and assembly. Besides, this structure allows one to reduce VSWR at the input port inside the entire frequency range during the accelerator operation by retuning cavities to adjust them flexibly to different beam loading conditions, while keeping the accelerating voltage within the tolerances required.

The author thanks Drs. G.Gurov and I.Sulygin for their interest to this work, and S.Kuznetsov and V.Kudryavtsev for valuable discussions.

5 REFERENCES

[1] V.V. Katalev et al, "The 200 MHz Accelerating Structure for UNK", EPAC-92, Berlin.

[2] D. Boussard, "Control of Cavities with High Beam Loading", IEEE Trans. on Nuclear Science, vol. NS-32, No.5, 1985.

[3] F. Pedersen, "A Novel RF Cavity Tuning Feedback Scheme for Heavy Beam Loading", IEEE Trans. on Nuclear Science, vol. NS-32, No. 5, 1985

[4] Jerome L. Altman, Microwave Circuits, New York, 1964