SLAC-PUB-2285
March 1979
(A)

# PULSED RF SYSTEMS FOR LARGE STORAGE RINGS†

P. B. Wilson‡

## I. Introduction

In this paper we consider the possibility that by using a pulsed rf system a substantial reduction can be made in the rf power requirement for the next generation of large storage rings. For a ring with a sufficiently large circumference, the time between bunch passages, $T_b$, can exceed the cavity filling time, $T_f$. As the ratio $T_b/T_f$ increases, it is clear that at some point the average power requirement can be reduced by pulsing the rf to the cavities. In this mode of operation, the rf power is turned on a filling time or so before the arrival of a bunch and is switched off again at the time of bunch passage. There is no rf energy in the accelerating structure, and hence no power dissipation, for most of the period between bunches.

For a pulsed system a structure is desired which requires the least stored energy per unit length, w, for a given accelerating gradient, $E_a$. A figure of merit for the structure in this case is*

$$k_1 = \frac{E_a^2}{4w} = \frac{\omega}{4}\left(\frac{r}{Q}\right) \quad , \qquad (1)$$

where r/Q is the shunt impedance per unit length divided by the unloaded Q. For a cw system a structure is desired which dissipates the least power per unit length, $P_1$, to achieve a given accelerating field. The shunt impedance per unit length, $r = E_a^2/P_1$, is the figure of merit in this case. A consideration of Eq. (1) shows that for a pulsed system cavity geometry is of primary importance, rather than wall losses. In addition, the figures of merit for the two kinds of structures scale differently with frequency:

$$k_1 \sim \omega^2 \quad \text{(pulsed)}$$
$$r \sim \omega^{1/2} \quad \text{(cw)} \quad .$$

There is a stronger incentive, therefore, to operate a pulsed system at a higher frequency.

## II. Pulsed System with No Beam Loading

Consider a constant impedance traveling-wave structure with attenuation parameter $\tau = \omega T_f/2Q$, where $T_f = L/v_g$ is the filling time. The peak energy gain for a structure of length L is[1]

$$\hat{V} = (rL\hat{P})^{1/2}\left[(2\tau)^{1/2}(1-e^{-\tau})/\tau\right] \quad ,$$

where $\hat{P}$ is the peak power from the rf source. The energy per pulse required to fill the structure is

$$W_p = \hat{P}T_f = \frac{\hat{V}^2}{\omega(r/Q)L}\left(\frac{\tau}{1-e^{-\tau}}\right)^2 \quad .$$

The average power delivered by the source is simply the energy per pulse divided by the time between bunches, or $\bar{P} = W_p/T_b$. Taking also the limit of small $\tau$ and introducing the structure parameter $k_1$ from Eq. (1), we obtain

$$\bar{P} = \frac{\hat{V}^2}{4k_1 LT_b}(1+\tau) \quad . \qquad (2)$$

The same result is obtained for small $\tau$ in the case of a constant gradient structure.

In the case of a standing-wave structure with filling time $T_f = (2Q/\omega)(1+\beta)^{-1}$, the peak voltage at time t is

$$\hat{V}(t) = (rL\hat{P})^{1/2}\left(\frac{2\beta^{1/2}}{1+\beta}\right)\left(1-e^{-t/T_f}\right) \quad ,$$

where $\beta$ is the coupling coefficient. The energy required to attain a voltage $\hat{V}$ at the end of a pulse of length $T_p$ is

$$W_p = \hat{P}T_p = \frac{\hat{V}^2}{\omega(r/Q)L}\left[\frac{T_p/T_f}{2(1-e^{-T_p/T_f})^2}\right]\left(1+\frac{1}{\beta}\right).$$

It is readily shown that the pulse energy is minimum if the pulse length is chosen to be $T_{po} \approx 1.257\,T_f$. At this pulse length, using also Eq. (1) and $\bar{P} = W_p/T_b$,

$$\bar{P}(\text{min}) = 1.228\,\frac{\hat{V}^2}{4k_1 LT_b}\left(1+\frac{1}{\beta}\right) \quad . \qquad (3)$$

The factor of 1.228 is due to the fact that in the standing-wave case there is an unavoidable transient reflected power.

For both the standing-wave and traveling-wave cases, it is seen that the average power is inversely proportional to the time between bunches. This raises the possibility that in a multi-bunch machine the accelerating voltage can be increased for the same average power by decreasing the number of bunches.

## III. Beam Loading in a Pulsed System

In the single-pass limit (fields in all modes die away between bunches) a phasor diagram for the fundamental mode can be drawn[2] as shown in Fig. 1.

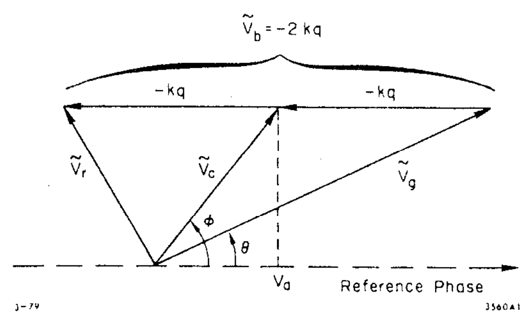


Fig. 1. Phasor diagram showing the superposition of the generator and beam-induced voltages for single-bunch beam loading.

In this diagram the reference phase is the phase of the peak accelerating voltage, $\theta$ is the phase of the generator voltage $\tilde{V}_g$ at bunch arrival, $\tilde{V}_c$ is the effective cavity voltage acting on the bunch, and $\phi$ is the synchronous phase angle. The total beam-induced voltage component is $\tilde{V}_b$ (the reference phase is chosen such that $\tilde{V}_b$ is in the negative-real direction), leaving a residual voltage $\tilde{V}_r$ in the cavity after the passage of the bunch. It can be shown[2] that the component of the beam-induced voltage acting on the bunch is $\tilde{V}_b/2 = -kq$, where $k = k_1 L$. Higher-order-mode losses in the rf structure are taken into account by the beam loading enhancement factor B, which is the ratio of the energy loss to all modes divided by the loss to the fundamental mode for a charge passing through an initially unexcited structure. The energy loss per turn to higher-order

† Work supported by the Department of Energy under contract number EY-76-C-03-0515.

‡ Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305.

* The structure constant $k_1$ has been defined to be consistent with $U_1 = k_1 q^2$, where $U_1$ is the energy lost per unit length to the fundamental mode by charge q in an initially unexcited structure. See also Ref. 2.

Presented at the 1979 Particle Accelerator Conference, San Francisco, California, March 12-14, 1979.

modes in the rf structure is $U_{hm} = (B-1)kq^2$. Thus the net accelerating voltage that must be provided by the rf system can be written

$$V_a = V_s + V_e + (B-1)\,kq$$

where $V_s$ is the synchrotron radiation loss per turn and $V_e = k_e q$ is the sum of all parasitic mode losses external to the rf structure. From this expression and Fig. 1, we have

$$V_g \cos\theta = V_a + kq = V_s + k_e q + Bkq$$

$$V_g \sin\theta = V_a \tan\phi \quad .$$

Squaring and adding the preceding two expressions to eliminate $\theta$ and setting $V_g = \hat{V}$ in Eqs. (2) and (3), the average power that must be delivered by the generator is

$$\bar{P} = \frac{C_s}{4k_1 LT_b}\left[V_a^2 \tan^2\phi + (V_a + kq)^2\right] \quad .$$

Here $C_s$ is a structure constant, equal to $(1+\tau)$ for the traveling-wave case and $1.23(1+1/\beta)$ in the standing-wave case. Normalizing to the average generator power, $P_o$, required to establish the energy gradient in the absence of a beam:

$$\frac{\bar{P}}{P_o} = \left[\frac{V_s + k_e q + (B-1)kq}{V_s}\right]^2 \sin^2\phi + \left[\frac{V_s + k_e q + Bkq}{V_s}\right]^2 \cos^2\phi \qquad (4)$$

$$P_o = \frac{C_s V_s^2}{4k_1\, LT_b \cos^2\phi} \quad . \qquad (5)$$

The preceding relations were derived for a single beam with charge q per bunch. For two equal beams in the standing-wave case, q must be replaced by 2q and B by $(B+1)/2$ (see Ref. 1). For the traveling-wave case, we assume that the structure acts independently on each beam. The total unloaded power given by Eq. (5) must then be doubled, while q and B in Eq. (4) remain the same.

The generator power can be minimized as a function of structure length for a given charge per bunch. The optimum length is

$$L_o = \frac{V_s + V_e}{k_1 q[(2B-1)\cos^2\phi + (B-1)^2]^{1/2}} \quad . \qquad (6)$$

## IV. Choice of Structure

A traveling-wave structure is advantageous in that there is no energy loss due to reflected power. A method for independently accelerating both $e^-$ and $e^+$ beams using the same traveling-wave structure is shown in Fig. 2.

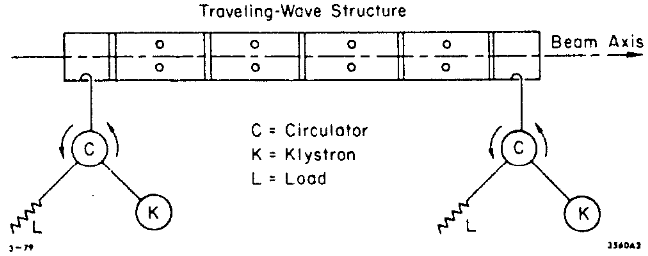


Fig. 2. System for using the same traveling-wave structure to accelerate both $e^+$ and $e^-$ beams.

The structure itself should have a high r/Q and a low parasitic mode loss parameter B. A high group velocity is also required to give a reasonable length of structure between feeds with low attenuation. One structure which seems to incorporate all these features is the jungle gym structure, illustrated in Fig. 3.

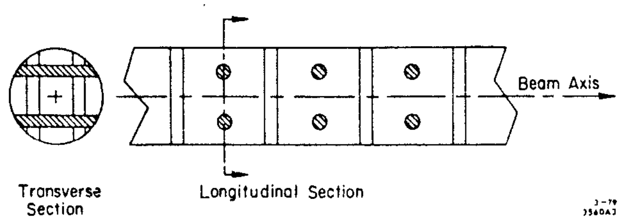


Fig. 3. Section of jungle-gym structure.

This structure was incorporated into a traveling-wave resonant ring and used as an rf cavity in the Cornell electron synchrotron.[3,4] The measured properties of the Cornell structure are: f = 714 MHz ($\pi/2$ mode), $Q = 1.8 \times 10^4$, $r/Q = 1400\ \Omega/m$, $k_1 = 1.6 \times 10^{12}$ V/C-m, $v_g/c = 0.22$.

The jungle-gym structure was also investigated (1957-59) at the Microwave Laboratory at Stanford.[5] A $k_1$ of about $2.1 \times 10^{12}$ V/C-m (normalized to 714 MHz) was obtained for the $\pi/3$ mode in a structure with a rectangular cross section at $v_g/c = 0.1$. This corresponds to an r/Q on the order of 1900 $\Omega$/m. At the same frequency, the present PEP structure would have an r/Q of about 1200 $\Omega$/m for an equivalent beam aperture ($2a \approx 7.0$ cm). Structure impedances must always be compared at the same beam aperture. The impedance in general falls off quite rapidly as the aperture is increased. A jungle-gym can be built at 700 MHz with a full aperture (measured along the diagonal of the central opening) of about 8.5 cm.

One significant advantage of the jungle-gym structure, apparent from the drawing in Fig. 3, is that the fabrication of the structure should be simple and inexpensive. The structure is basically a hollow pipe with round bars placed across it at periodic intervals. By making the bars hollow, they can easily be water cooled. There are, of course, no tuners. Operational experience at Cornell has also shown[4] that, compared to conventional cavities, the structure is much less susceptible to multipactoring. In addition, higher-mode losses should be quite low in this structure. The transverse bars are clearly a small discontinuity compared to the dividing walls between cells in a conventional standing-wave structure. Preliminary measurements give a beam loading enhancement factor B = 1.35 at a bunch length of 2.3 cm for the Cornell structure. This can be compared to B = 2.5 for the PEP or PETRA cavities at the same bunch length.

## V. Comparison of Pulsed and CW Systems

For a traveling-wave system capable of accelerating two beams in opposite directions, the average power required will be twice that given by Eq. (5). For a cw standing-wave system, the average power required is $\bar{P}(cw) = \hat{V}^2/Lr_{sw}$. Therefore

$$\frac{\bar{P}(\text{pulsed})}{\bar{P}(cw)} = \frac{(1+\tau)r_{sw}}{2k_1 T_b} \sim \omega^{-3/2} \quad .$$

Let us compare systems at 700 MHz, taking $\tau = 0.2$ and $k_1 = 2.1 \times 10^{12}$ $\Omega$/m-sec for a $\pi/3$-mode jungle-gym structure. A PEP or PETRA-type standing-wave structure might have a shunt impedance of 35 M$\Omega$/m at this frequency. Using these values in the preceding expression, we find that $\bar{P}(\text{pulsed}) = \bar{P}(cw)$ at $T_b \approx 10\ \mu s$. The next generation of large storage rings will have bunch passage times in the range 20-100 $\mu$s. A pulsed rf system at 700 MHz should therefore be advantageous.

## VI. Application to LEP-70

The design concepts of pulsed rf have been applied[6,7] to machines with average radii of 1.7 km and 3.5 km. Table I summarizes the results for the second case -- a machine with the lattice and beam parameters of the proposed LEP-70 storage ring.[8] A total average rf power of 64 MW has been assumed, compared to 74 MW for the cw system is the LEP-70 design. Examples of pulsed systems designs are given at 500 MHz and 700 MHz using estimated jungle-gym structure parameters for the $\pi/2$ mode ($v_g/c = 0.2$) and the $\pi/3$ mode ($v_g/c = 0.1$). The synchronous phase angle for LEP-70, using a 350 MHz rf system, is 30° off crest. This angle has been increased to 33° at 500 MHz and 37° at 714 MHz to maintain an adequate quantum lifetime.

| | 714 MHz Systems | | 500 MHz Systems | |
|---|---|---|---|---|
| **Structure Parameters** | | | | |
| $v_g/c$ | 0.20 | 0.10 | 0.10 | 0.10 |
| Section Length (m) | 60 | 60 | 60 | 45 |
| Filling Time (μs) | 1.0 | 2.0 | 2.0 | 1.5 |
| Attenuation Parameter $\tau$ | 0.125 | 0.25 | 0.15 | 0.11 |
| B Factor ($\sigma_z$ = 2.3 cm) | 1.35 | 1.53 | 1.53 | 1.53 |
| Total Structure Length (m) | 1920 | 1920 | 1920 | 2880 |
| **Klystron Requirements ($N_b$ = 4/1)*** | | | | |
| Klystrons per Feed | 1    2 | 2 | 1    2 | 1 |
| Total No. of Klystrons | 64    128 | 128 | 64    128 | 128 |
| Max. Average Power per Klystron (kw) | 1000    500 | 500 | 1000    500 | 500 |
| Max. Peak Power per Klystron (MW) | 18/74    9.3/37 | 4.6/18.5 | 9.3/37    4.6/18.5 | 6.2/25 |
| Duty Cycle (%) | 5.4/1.35 | 10.8/2.7 | 10.8/2.7 | 8.1/2.0 |
| Pulse Length (μs) | 1.0 | 2.0 | 2.0 | 1.5 |
| Repetition Rate (kHz) | 54/13.5 | 54/13.5 | 54/13.5 | 54/13.5 |
| **70 GeV Operation (10.5 mA/beam)** | | | | |
| Ave. Generator Power $P_g$ (MW) | 38.2 | 47.7 | 46.8 | 41.3 |
| Higher Mode Power $P_{hm}$ (MW) | 4.4 | 8.8 | 4.2 | 6.3 |
| Cavity Dissipation $P_d$ (MW) | 5.9 | 13.6 | 9.3 | 5.6 |
| Load Dissipation $P_\ell$ (MW) | 7.8 | 5.2 | 13.2 | 9.3 |
| Opt. Structure Length $L_o$ (m) | 2780 | 1840 | 3730 | 3730 |
| Net Beam Efficiency $P_b/P_g$ (%) | 53 | 42 | 43 | 49 |
| **Top Energy Operation** | | | | |
| Unload Energy (GeV) ($N_b$ = 4/2/1) | 86/94/102 | 88/94/104 | 82/89/97 | 86/94/102 |
| Energy (GeV) for $\mathscr{L} \approx 10^{31}$ ($N_b$ = 1) | 98 | 100 | 93 | 98 |

* $N_b$ = number of bunches per beam

Table I

It is seen that several of these systems designs can reach an operating energy of over 80 GeV with 4 bunches per beam and a top energy of about 100 GeV with one bunch per beam. At 70 GeV the rf system must deliver 20.1 MW to the beam. The net efficiency for power transfer to the beam is seen to range from 42% to 53%. For 70 GeV operation, $P_{hm}$ is the power transferred to high-order modes in the rf structure, $P_d$ is the fundamental mode power dissipated in the structrue, and $P_\ell$ is the fundamental mode power dissipated in the circulator loads.

It is difficult to design a high efficiency pulsed klystron with a peak output power greater than about 20 MW.[9] On this basis, the high group velocity design in the first column appears to be ruled out. In the other columns, only the systems using 128 tubes meet or come close to meeting this restriction on peak power. The peak power can be reduced by increasing $\tau$.

## VII. Conclusion

A pulsed rf system can decrease the average power consumption or increase the top operating energy of a large storage ring. The operating frequency must, however, be at least 500 MHz in order to obtain a significant advantage from a pulsed system. The highest energy operation is achieved at the expense of reducing the number of bunches per beam.


## Acknowledgement

Discussions with a number of colleagues at CERN and SLAC have been helpful in motivating or clarifying various aspects of this study. I would like, in particular to acknowledge D. Farkas, H. Hogg, A. Hutton, G. Loew, R. Miller, D. Ritson and H. Wiedemann. Thanks also to J. Weaver and J. Styles for their measurement of the B factor for the jungle-gym structure.


## References


1. G. A. Loew and R. B. Neal, Linear Accelerators, P. Lapostolle and A. Septier, eds. (North Holland, 1970), Sec. B-1.1.
2. P. B. Wilson, PEP-276, SLAC, Stanford (December 1978); also CERN-ISR-TH/78-23 (October 1978).
3. M. Tigner, IEEE Trans. Nucl. Sci. NS-18, No. 3, 249 (1971).
4. J. L. Kirchgessner and M. Tigner, IEEE Trans. Nucl. Sci. NS-20, No. 3, 928 (1973).
5. Microwave Laboratory, Stanford University, Report Nos. ML-416 (April 1957), ML-432 (July 1957), ML-504 (April 1958), ML-520 (July 1958), ML-557 (Nov. 1958) and ML-581 (Feb. 1959).
6. D. Ritson, PEP-280, SLAC, Stanford (March 1979).
7. P. B. Wilson, PEP-282, SLAC, Stanford (Feb. 1979).
8. LEP Design Study, CERN/ISR-LEP/78-17 (August 1978).
9. G. Konrad and J. Lepacqz, private communication.