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USE OF A FIRST-HARMONIC RF SYSTEM IN THE NSLS BOOSTER

NOTICE

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USE OF A FIRST-HARMONIC RF SYSTEM IN THE NSLS BOOSTER

Introduction

In order to capture and accelerate the maximum amount of beam injected into the booster from the linac and to put all of this beam into one bucket of the WUV or the X-Ray Ring, several scenarios involving a first-harmonic RF system can be considered:

- a. accelerate with 5 full buckets (with the present 5th harmonic system) and coalesce the 5 bunches into one 1st harmonic bucket at flat-top, or possibly before flat top, or
- b. accelerate with a first harmonic (10.57 MHz) system all the way, or
- c. accelerate with a first harmonic until the bunch has damped sufficiently to transfer to one of the fifth-harmonic buckets (suggested by Galayda to ease the voltage requirements on the first harmonic system).

The capture efficiency at injection should be independent of the harmonic number of the RF system, unless there are deleterious beam-cavity interactions, in which case the first-harmonic system using ferrite could have an advantage because of its lossy characteristics at high frequencies.

The acceleration efficiency should also be independent of harmonic number except at high beam intensities where collective instabilities can occur. In this domain the system with lower peak beam current would be favored. As will be seen, this consideration favors the fifth-harmonic acceleration system.

Procedure

Several acceleration cycles were examined for the evolution of the bunch parameters throughout the acceleration cycle. Adiabatic damping, radiation damping, and quantum excitation effects were included.

In each case a linear energy ramp from 75 MeV (injection) to 750 MeV in 0.4 second was assumed. Also a linear ramp in peak RF voltage from V_0 (injection) to 22 kV at 750 MeV (overvoltage factor of 1.5) was used. The initial RF voltage V_0 depends on the harmonic number h and the area of the beam in longitudinal phase space A_g . Two harmonics ($h=1$ and 5) and two phase-space areas were used, the two areas corresponding to effective linac energy spreads of ± 0.5 and $\pm 0.88\%$. The corresponding voltages and bucket areas are:

<u>h</u>	<u>ΔE_L</u>	<u>V_0</u>	<u>$A_R (=A_{BR})$</u>
1	$\pm.5\%$	1.16KV	4.71 MeV rad
5	$\pm.5$	4.22	4.71
1	$\pm.88$	2.2	8.29
5	$\pm.88$	11.0	8.29

The formulas used are well known but are listed for completeness in Table 1. To get the phase and momentum widths of the beam bunches as they damped, the tables given in "Areas and Bunching Factors of Partially Filled Buckets" by F. T. Cole and P. L. Morton (LBL unpublished note, UCID 10130, 1964) were very useful. A plot of the bunching factor versus fractional bucket area for several synchronous phases is shown in Figure 1.

Results

Case 1.5 ($h=1$, $\Delta E_L = \pm.5\%$)

t	E	U_0	$\left(\frac{\Delta E}{\Delta N}\right)_{tot}$	V	ϕ_s	A_0	D	$\left(\frac{\Delta\phi}{2\pi}\right)_B$	$\left(\frac{\Delta\phi}{2\pi}\right)_B$	v_s	I_p
sec	MeV	KeV	KeV	KV		Mev-rad		A+D	Q $\times 10^{-4}$		mA
0.0	75	0.0015	0.162	1.16	8^0	6.02	1.00	0.78	0.004	4.9	37
0.01	91.9	0.0033	0.163	1.68	5.6	8.02	1.00	0.61	0.005	5.3	44
0.05	159	0.030	0.192	3.77	2.9	15.8	0.98	0.40	0.007	6.1	65
0.1	244	0.165	0.325	6.37	2.9	25.5	0.89	0.29	0.011	6.4	90
0.15	328	0.538	0.698	8.98	4.5	35.1	0.68	0.19	0.014	6.5	140
0.2	413	1.35	1.51	11.58	7.5	44.7	0.38	0.092	0.018	6.6	278
0.25	497	2.83	2.99	14.19	12.2	54.2	0.13	0.028	0.021	6.6	910
0.3	581	5.29	5.45	16.79	18.9	63.8	0.022	0.004	0.025	6.5	1000
0.35	666	9.14	9.30	19.40	28.7	73.4	0.0014	0.00025	0.030	6.3	830
0.4	750	14.7	14.86	22.00	42.5	82.9	0.000025	0.000004	0.037	5.8	690

$\left(\frac{\Delta\phi}{2\pi}\right)_B$ beam width due to adiabatic and radiation damping only
A+D

$\left(\frac{\Delta\phi}{2\pi}\right)_B$ beam width due to quantum excitation
Q

Case 5.5 ($h=5$, $\Delta E_L = \pm 0.5\%$)

t	E	V	ϕ_s	A_o	v_s	$\left(\frac{\Delta\phi}{2\pi}\right)_B$	$\left(\frac{\Delta\phi}{2\pi}\right)_B$	I_p
sec	MeV	KV		Mev-rad	$\times 10^{-3}$	A+D	Q	mA
0	75	4.22	2.2 ⁰	5.14	2.09	0.89	0.005	33
0.01	91.9	4.66	2.0	5.98	1.99	0.76	---	37
0.05	159	6.44	1.7	9.25	1.77	0.55	0.013	48
0.1	244	8.66	2.2	13.3	1.66	0.41	---	64
0.15	328	10.89	3.7	17.3	1.61	0.27	0.029	97
0.2	413	13.11	6.6	21.3	1.57	0.133	0.037	192
0.25	497	15.33	11.3	25.2	1.53	0.041	0.046	555
0.3	581	17.56	18.1	29.2	1.50	0.006	0.055	465
0.35	666	19.78	28.1	33.2	1.43	0.0004	0.066	385
0.4	750	22.0	42.5	37.1	1.30	0.000	0.082	313

Case 1.88 ($h = 1$, $\Delta E_L = \pm 0.88\%$) (160 eV/turn acceleration neglected)

t	E	V	ϕ_s	A_o	v_s	$\left(\frac{\Delta\phi}{2\pi}\right)_B$	$\left(\frac{\Delta\phi}{2\pi}\right)_B$	I_p
sec	MeV	kv		Mev-rad	$\times 10^{-4}$	A+D	Q	mA
0	75	2.2	0.04 ⁰	8.29	6.75	1.0	---	31
0.01	91.9	2.7	0.07	10.17	6.75	0.77	---	36
0.05	159	4.68	0.37	17.6	6.75	0.52	---	50
0.10	244	7.16	1.3	27.0	6.75	0.37	---	70
0.15	328	9.62	3.2	36.3	6.75	0.24	---	108
0.2	413	12.11	6.4	45.7	6.73	0.12	---	216
0.25	497	14.58	11.2	55.0	6.69	0.037	---	680
0.3	581	17.04	18.1	64.3	6.58	---	0.025	980
0.35	666	19.54	27.9	73.7	6.34	---	0.030	810
0.40	750	22.0	41.9	82.9	5.82	---	0.037	660

Case 5.88 ($h = 5$, $\Delta E_L = \pm 0.88\%$, 160 eV/turn acceleration neglected)

t	E	V	ϕ_s	A_0	v_s	$\left(\frac{\Delta\phi}{2\pi}\right)_B$	$\left(\frac{\Delta\phi}{2\pi}\right)_B$	I_p
sec	MeV	kv		Mev-rad	$\times 10^{-3}$	A+D	Q	mA
0	75	11.0	0.01 ⁰	8.29	3.4	1.00	---	31
0.01	91.9	11.3	0.02	9.30	3.1	0.86	---	32
0.05	159	12.4	0.14	12.8	2.5	0.64	---	43
0.1	244	13.8	0.69	15.9	2.1	0.51	---	53
0.15	328	15.1	2.0	20.3	1.9	0.34	---	78
0.2	413	16.5	4.7	23.8	1.8	0.18	---	150
0.25	497	17.9	9.1	27.2	1.7	0.055	---	485
0.3	581	19.3	16.0	30.5	1.6	---	0.056	438
0.35	666	20.6	26.3	33.9	1.5	---	0.066	362
0.40	750	22.0	41.9	37.1	1.3	---	0.080	313

Note that in each case the beam damps until it reaches an equilibrium with quantum excitation, which occurs between 0.25 and 0.30 sec (500 to 580 MeV). See Fig. 2. Thus the peak current rises to its maximum value at this time, after which it decreases due to increased beam length caused by greater energy spread by quantum excitation at higher energy.

The maximum peak current is about 1.0 Ampere for each of the first-harmonic scenarios and about 0.5 Ampere for each of the fifth-harmonic cases, thus favoring the fifth-harmonic system. However, the significance of this advantage at this current level is not clear.

Bunch Coalescence

The coalescence maneuver is simply to snap on the first-harmonic voltage to provide a bucket that encompasses the 5 bunches accelerated by the fifth-harmonic accelerating system. The pertinent parameters are shown as a function of time in the acceleration cycle.

We note that coalescence at flat-top is not efficient because the 10MHz bucket at that time is only $0.4 \times 2\pi$ in length. In order to make the transfer as efficient and as late as possible, we consider a first harmonic bucket at 22kv (the maximum assumed). To capture the 5 bunches, the bucket width must be greater than $0.8 + \left(\frac{\Delta\phi}{2\pi}\right)_B$. Thus the latest time for this transfer is about 0.22 sec (about 450 MeV). However, such a transfer would probably be lossy because the end bunches would rotate in phase space to the top of the RF bucket which at this time is about $\pm 1.5\%$ in half height (bottom curve), thus exceeding the $\pm 0.5\%$ energy aperture of the booster.

The graph shows also that the transfer of 4 bunches can occur as late as 0.33 seconds, at which point the bucket half height is about $\pm 0.7\%$.

Conclusion

The use of a first-harmonic acceleration system seems to be the simplest most efficient way of achieving a single bunch with the maximum current.

TABLE 1

Formulas Used

Energy ramp	$E = 75 + 1687.5t$ MeV
Voltage ramp	$V = V_0 + (22.5t) \times 10^4$ sec
Energy damping factor	$D = \Delta E / \Delta E_0$
	$\frac{d\Delta E}{dt} = - \frac{\Delta E}{\tau_E}$
	$\tau_E = 12.9 \times 10^{-3} \left(\frac{700}{E}\right)^3$ sec
	$\ln D = 1.06 \times 10^{-3} [1 - (1 + 22.5t)^4]$
Natural energy width from quantum excitation $(\sigma_E/E)_n$	
	$(\sigma_E/E)_n = 6.85 \times 10^{-4} \left(\frac{E}{750}\right) = 6.85 \times 10^{-5} + 1.539 \times 10^{-3}t$
Radiation loss per turn	$U_0 = 14.7 (E/750)^4$ keV
Energy gain per turn for acceleration	160 eV/turn
Bucket area	$A_{BK} = A_0 \alpha(\phi_s)$ A_0 = Stationary bucket area ($\phi_s=0$) $= 16 \left(\frac{eVE}{2\pi h\alpha}\right)^{1/2}$ α = compaction factor = 0.0977 $\alpha(\phi_s)$ = "moving bucket factor"
Bucket half height	$(\Delta E/E)_{BK} = \left(\frac{2eV}{\pi E h\alpha}\right) F^{1/2}(\phi_s)$
Beam area at injection	$F^{1/2}(\phi_s) = [\cos \phi_s - (\pi/2 - \phi_s) \sin \phi_s]^{1/2}$ $A_B = 4\pi \Delta E_L$ ΔE_L = linac half-energy spread
Beam width (full)	$\left(\frac{\Delta\phi}{2\pi}\right)_B = 4B/\pi$ (for bucket less than 3/4 full) $B \equiv$ bunching factor = I_0/I_p I_0 = average beam current = 20 mA also $\left(\frac{\Delta\phi}{2\pi}\right)_B = \left(\frac{h\alpha}{v_s \pi}\right) \left(\frac{\sigma_E/E}{\left(\frac{\alpha h V \cos \phi_s}{2\pi E}\right)^{1/2}}\right)^{1/2}$
Synchrotron tune

FIGURE 1

α_{11}

FIGURE 3