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TITLE: A MULTIDIMENSIONAL STUDY OF A 50-MeV, 1500-RAD/PULSE
RADIOGRAPHIC LINAC, USING THE STAGGER TUNING CONCEPT

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Summary

Stagger tuning of accelerator cavities, or blocks of cavities, can significantly enhance the achievable charge transfer through an electron linac operating in the stored-energy mode. The output bremsstrahlung flux can be increased over a conventional approach by an order of magnitude without any significant degradation in emittance growth or energy spread. Given a suitable injector, a 1500-rad/pulse, 50-MeV radiographic linac appears to be practical at a 400-MHz operating frequency; a 150-rad/pulse, 50-MeV radiographic linac will operate at 1300 MHz. A multidimensional study was made using the PARMELA code where several parameters, including beam current, synchronous phase angle, and beam radius, were varied while observing the effects on emittance and transmission efficiency.

Introduction

High-resolution radiographic experiments require that the peak radiation flux be concentrated into a small region. This implies that the suitable electron beam source for the bremsstrahlung radiation be focused to as small a cross-sectional area as possible on the bremsstrahlung-producing target.

The bremsstrahlung flux from a targeted electron beam linac is

$$P = \frac{1.1 \times 10^{-3} K_0 E_{kp} Q (\Delta U/U) W^{2.8}}{2\pi f T \cos \phi (E_{\max}/E_0)}$$

in rads/pulse on-axis at 1 m, where f is the linac operating frequency in MHz, Z is the accelerating structure shunt impedance in $M\Omega/m$, Q is the dimensionless quality factor, T is the electron transit-time factor, $(E_{\max}/E_0)$ is the ratio of maximum surface electric field to average axial electric field, ϕ is the synchronous phase angle, W is the linac output electron kinetic energy in MeV, $\Delta U/U$ is the fraction of stored energy extracted, E_{kp} is the Kilpatrick's maximally allowed frequency-dependent surface electric field in MV/m, K_0 is the bravery factor, in excess of E_{kp} , one is ready to assume.

One would like to select an accelerating structure that maximizes the ratio of stored energy to the energy extracted. Simultaneously, one would like to operate at the highest frequency possible in the interest of size and cost. This study was done with a pillbox cavity in the TM_{02} mode because it optimized the relevant parameters, and this mode was sufficiently isolated, thus reducing the possibility of higher order modes being excited. The frequency f was chosen from the availability of "stock" klystrons with frequency and power combinations of 200 MHz (5 MW) and 400 MHz (20 MW).

Once frequency is determined, E_{kp} can be found from iteratively solving $f = 1.643 E_{kp}^{2/3} \exp(-8.5/E_{kp})$. The Kilpatrick field, E_{kp} , generally is conceded to be

somewhat conservative, thus the introduction of K_0 . Sparking experiments indicate that one can exceed E_{kp} by as much as a factor of 2. Here, K_0 did not exceed 1.75. The term left to maximize is $(\Delta U/U)/\cos \phi$. Usually, $\phi = 0$ in a stored-energy design; and $(\Delta U/U)$, the fractional energy extracted, is limited by the allowable output energy spread. This is because with any given beam-transport system, the spot size on target is dependent on the beam's energy spread. For a 5% energy spread, from $\Delta W/W \sim 1/2 (\Delta U/U)$, $\Delta U/U$ can be no more than 10%. We can increase the ratio $\Delta U/U$ by using the energy-gain equation $W = ETL \cos \phi$; where W is the electron energy gain, E is the peak accelerating field at any instant during the beam pulse, T is the transit-time factor, L is the accelerator length, and ϕ is the reference phase angle. The latter two terms, T and L , are design parameters and cannot be varied. As the initial electrons of the macropulse begin to deplete the stored energy of the cavity, the electric field begins to droop. The electron energy spread caused by this field droop can be minimized by setting $W_i = W_f$, where i and f refer to the initial and final values of W , E and ϕ . Then $E_i \cos \phi_i = E_f \cos \phi_f$, which leads to

$$\phi_f = \cos^{-1} \frac{\cos \phi_i}{[1 - (\Delta U/U)]^{1/2}}$$

with the operational requirement that ϕ be varied from ϕ_i to ϕ_f in consonance with the field droop. Although this in principle minimizes the energy spread caused by field droop, another source of spread is introduced. For a micropulse of width Δ , a nonzero reference phase angle ϕ has an associated energy spread of

$$\frac{\Delta W}{W} = 2 \tan \phi \sin \frac{\Delta}{2}$$

This source of spread, however, can be minimized by operating alternate cavities or blocks of cavities at plus or minus ϕ 's.

Ideally, one would phase modulate the two drive sources from $-\phi_i$ to $-\phi_f$ and from $+\phi_i$ to $+\phi_f$, in consonance with the field droop. This is not a trivial task on the required time scale. A practical solution is to operate alternate cavities or blocks of cavities at a frequency above and below ($\pm \Delta f$) the reference (injector) frequency by an amount

$$\Delta f = \frac{\phi_i - \phi_f}{360 t_p}$$

where t_p is the beam pulse duration in μs , Δf in megahertz and ϕ in degrees.

Accelerator Data

This study was facilitated by the simplifying assumption of axial symmetry of beam, accelerating

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structure, and focusing elements to eliminate one of the transverse dimensions. An injector was assumed that could deliver a pulse of particles with 5.0-MeV mean energy, a $\pm 5\%$ energy spread, and a Courant-Snyder parameter $\alpha = 0$ (that is, an upright phase-space ellipse). No attempt was made to optimize the output by varying the position of the beam waist. The normalized emittance (phase-space ellipse area/ π) was taken to lie between the values determined by Samuel Penner, National Bureau of Standards, Washington, DC, and the Los Alamos 20-MeV free-electron-laser linac, heavily weighted in favor of the Penner model for a conservative estimate.

Normalized emittance at 5 MeV is $\Sigma_5 = 4\pi^2 I / (B\gamma)_5$ in cm-mrad, where I is the beam current in A; and $(B\gamma)_5 = 10.78$, the relativistic correction for electrons with a 5-MeV kinetic energy. The input Courant-Snyder $\beta = R^2 / \Sigma_5$ in cm/rad, where R is the initial beam radius in cm.

The stagger-tuning principle rests on correcting the energy spread and emittance growth introduced by operating one or more consecutive accelerating cells at a nonzero reference angle ($-\phi$), by operating the next consecutive one or more cells at the opposite synchronous angle ($+\phi$).

Several configurations of cell-groupings were tried; the most notable was $[-\phi, +\phi]$ and $[-\phi, +\phi, +\phi, -\phi]$. Other groupings tried were $[-\phi, -\phi, +\phi, +\phi]$ and $[-\phi, -\phi, -\phi, +\phi, +\phi, +\phi]$. The latter ones were tried in an attempt to allow a single-frequency generator to be driven at full power by driving, at the same frequency, as many consecutive cells as possible. The results showed a significant degradation in the output emittance to offset the marginal benefits. The first set of cell groupings can be economically employed if cells of the same frequency are fed by a common manifold.

The computer code PARMELA was used in this study. The program randomly scatters 180 electrons with uniform phase and random energy spread within an ellipse and adds one more electron precisely centered as the reference particle. The program computes the trajectories and returns, among other things, the rms emittance that is related to the normalized emittance by

$$\frac{\Sigma_{rms}}{(B\gamma)_5} = 6 \cdot 1000 \Sigma_5 \quad \text{in units of } \pi \text{ cm-mrad}$$

and the Courant-Snyder phase-space ellipse parameters.

Summary of Results

The two best configurations of cell groupings at 400 and 1300 MHz are the ones having a unit structure $[-\phi, +\phi]$ and $[-\phi, +\phi, +\phi, -\phi]$, the latter having a consistently lower emittance over the former. Because the minimum spot size $x_{max} = (\Sigma + R_f)^{1/2}$ is a function of emittance and $1/R$ before the beam enters the focusing elements, this study has concentrated on attaining the lowest emittance after passing through the linac, which should give the smallest focused spot size on target and the least divergence.

400 MHz

A 1500-rad/pulse flux with a 50-MeV bremsstrahlung end-point energy requires 24 μ C of 50-MeV electrons to be deposited on the target in the required time frame. If the desired pulse time is 100 ns, the corresponding beam current is 240 A.

The two groupings "x" and "xx", where the former is the grouping $[-\phi, +\phi]$ and the latter is $[-\phi, -\phi, +\phi, +\phi]$, have an emittance minimum at $\phi = 60^\circ$ for $R = 2$ cm (Fig. 1) and both have 100% transmission. Series "xx" has a 20% better emittance than "x" in the region of interest. For $R = 1$ cm, transmission drops below 90% for $I > 200$ A and $\phi < 40^\circ$. For $R = 3$ cm, a severe rise in emittance occurs for $\phi > 50^\circ$. Transmission for $R = 3$ cm and $\phi = 50^\circ$ is 100%.

Concerning the emittance as a function of initial beam radius, $R = 1$ cm has the lowest emittance for $I < 100$ A, $R = 2$ is better for $40 < I < 190$ A, and $R = 3$ cm has a lower value in the $190 < I < 300$ A region (Fig. 2).

SERIES XX

$R = 2.00$

Fig. 1. Emittance vs synchronous phase angle and current at 400 MHz and $R = 2$ cm.

Fig. 2. Emittance vs current for $R = 1, 2, 3$ cm at 400 MHz.

1300 MHz

A 150-rad/pulse flux with a 50-MeV bremsstrahlung end-point energy requires 2.4 μC of 50-MeV electrons to be deposited on target in the required time frame. If a 100-ns pulse is desired, the corresponding beam current is 24 A.

Again the same two groupings are discussed. At this frequency the most important factor is the transmission rate that is appreciably depleted for increasing current. For $R = 0.25$ cm, transmission is $>90\%$ only for $I < 5$ A. At $R = 0.5$ cm, the transmission is at the tolerable level for $I < 30$ A (Fig. 3). Finally for $R = 1$ cm, transmission is $>90\%$ for $I < 60$ A and $\phi > 50^\circ$ (Fig. 4). Figure 5 shows emittance as a function of I for each R . The grouping $[-\phi, +\phi]$ has a 2-5% better transmission. However, $[-\phi, -\phi, +\phi, +\phi]$ has a 20% lower emittance.

A plausible explanation for the phenomenon of why the synchronous angle pattern $[-\phi, +\phi, +\phi, -\phi]$ has a consistently lower emittance over that of $[-\phi, +\phi]$ for the same number of cells suggests that, for the latter, the leading particles experience the extreme nonlinear energy displacement from the reference-particle energy every other cell; whereas, in the former, the leading particles are only subject to extreme conditions every fourth cell, and alternately, the trailing particles now also experience these conditions in the intervening period.

SERIES UU

Fig. 3. Transmission vs current and synchronous phase angle at 1300 MHz and $R = 0.5$ cm.

SERIES UU

$R = 1.00$

Fig. 4. Transmission vs current and synchronous phase angle at 1300 MHz and $R = 1$ cm.

Fig. 5. Emittance vs current for $R = 0.25, 0.5$, and 1.0 cm at 1300 MHz.