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Beam Dynamics Issues in an Extended Relativistic Klystron*

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Preliminary studies of beam dynamics in a relativistic klystron were done to support a design study for a 1 TeV relativistic klystron two-beam accelerator (RK-TBA), 11.424 GHz microwave power source. This paper updates those studies. An induction accelerator beam is modulated, accelerated to 10 MeV, and injected into the RK with a rf current of about 1.2 kA. The main portion of the RK is the 300-m long extraction section comprised of 150 traveling-wave output structures and 900 induction accelerator cells. A periodic system of permanent quadrupole magnets is used for focusing. One and two dimensional numerical studies of beam modulation, injection into the main RK, transport and longitudinal equilibrium are presented. Transverse beam instability studies including Landau damping and the "Betatron Node Scheme" are presented.

I. BACKGROUND

A preliminary design report (PDR) by a joint LBL-LLNL team investigated an rf power source for the NLC linear collider. [1] This design promises to be competitive both in cost and total efficiency with systems based on conventional klystrons using pulse compression. However, it will be necessary to transport the modulated induction beam through a 300-m relativistic klystron to achieve the high efficiency. Thus, an important part of the PDR studies was simulating the motion of the beam. Two codes developed at LLNL were used for these simulations: RKS2 Code [2] is a 2-1/2 D PIC code with a coupled cavity circuit model used to simulate the interaction of the beam with the operating field, TM_{01} mode, while OMICE [3] is a slice code with a coupled cavity circuit model used to simulate the transverse dynamics of the beam interacting with a dominant dipole mode.

II. LONGITUDINAL DYNAMICS

The longitudinally dynamics that is acceptable for an extended RK can be achieved in the following way:

(1) In the main RK section the rf output cavities are inductively detuned (i.e. the phase velocity, v_{ph}, of the 3-cell traveling-wave structures (TWSs) is made faster than the velocity of the particles) to counter the debunching effects caused by space-charge and rf-induced energy spread. In this scheme the particle bunch lags behind the decelerating crest of the wave, with the particles at the bunch tail losing the least energy. Kinematics lead to a 'catching up' mechanism and subsequent synchrotron oscillation in stable rf buckets. The RKS simulations show stable propagation through 150 cavities (Figure 1). For comparison, cavities with no inductive detuning are shown to result in particle debunching after a few cavities.

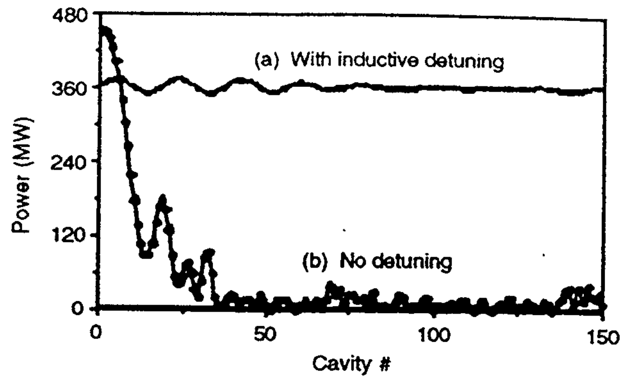

Figure 1. Power extraction from 150-cavities in an extended RK: (a) with inductive detuning ($v_{ph} = 1.33c$); (b) no detuning ($v_{ph} = 1.0c$).

(2) Before the main RK there is a chopper section and an 'adiabatic capture' section, which serve to modulate an initial DC beam into a train of tight bunches. These have the desired properties for beam transport and power extraction in the main RK. The chopper, based on the original Choppertron [4], should generate cleanly separated microbunches at 11.4 GHz with the length of the bunches equivalent to about 240° in longitudinal phase space. In the 'adiabatic capture' region, the microbunch lengths are further reduced by a number of (highly inductive) idler cavities, to 70° [1] which is the desired bunch length for the main RK. In addition to microbunch sharpening, this section also serves to provide the energy transition from 2.5 to 10 MeV [1] with the beam continuously accelerated by the induction machine between the bunching cavities.

(3) At the end of the RK is an 'afterburner' section which is to increase overall system efficiency by extracting more power out of the still bunched beam that exits the main RK (without reaccelerating it). The spacing and the impedances of the extraction cavities in this section are varied to compensate the continuous decline of the average energy of the beam as well as changes in the rf bucket.

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III. TRANSVERSE DYNAMICS

The primary issue for transverse dynamics is beam breakup (BBU) caused by the excitation of higher order modes in beam line structures. The PDR identified two components as sources of BBU. The first is the 900 induction cells in the RK with a trapped resonant mode near 4 GHz. A highly damped, conventional cell design described in the PDR has a transverse impedance less than 4 kΩ/m. This value is acceptably low, with Landau damping from the predicted energy spread, to avoid BBU.

The output structures are a greater difficulty. The "Betatron Node Scheme," that relies on the RK's strong periodic quadrupole focusing, is used to suppress BBU. The technique is described in the following example: A monoenergetic beam describes a betatron oscillation under the influence of a periodic focusing system. Passing through a series of thin cavities, the transverse position of individual electrons is unchanged. However, the transverse momentum increases by $\Delta p_x = Rx$, where R is an integral operator. The position and momentum from the exit of one cavity to the next is related through the following matrix transformation.

$$\begin{pmatrix} x \\ p_x \end{pmatrix}_n = \begin{bmatrix} 1 & 0 \\ R & 1 \end{bmatrix} \begin{bmatrix} \cos(\theta) & \frac{1}{\omega_\beta}\sin(\theta) \\ -\omega_\beta \sin(\theta) & \cos(\theta) \end{bmatrix} \begin{pmatrix} x \\ p_x \end{pmatrix}_{n-1}. \quad (1)$$

The first matrix represents the momentum change, and the second describes the betatron motion. If the phase advance, θ, is 2π between all cavities, the position and momentum at the n^{th} cavity can be related to the initial conditions:

$$\begin{pmatrix} x \\ p_x \end{pmatrix}_n = \begin{bmatrix} 1 & 0 \\ R & 1 \end{bmatrix}^n \begin{pmatrix} x \\ p_x \end{pmatrix}_0 = \begin{bmatrix} 1 & 0 \\ nR & 1 \end{bmatrix} \begin{pmatrix} x \\ p_x \end{pmatrix}_0. \quad (2)$$

Equation (2) indicates that the growth in the transverse momentum, and, therefore, the maximum displacement, increases linearly with the number of cavities. For θ not equal to an integral multiple of π, the growth can be exponential with the number of cavities [5]. While our design has a periodic structure, strong ppm focusing, and a constant average beam energy, there will be energy spread, variation in average energy, errors in the focusing system, and extended cavities. Numerical studies were performed to determine tolerances for realistic conditions. Using reasonable design parameters [6], errors of ± 1.5 % in the magnetic focusing and/or average energy are acceptable. In Fig. 2 the result of one of these studies is shown.

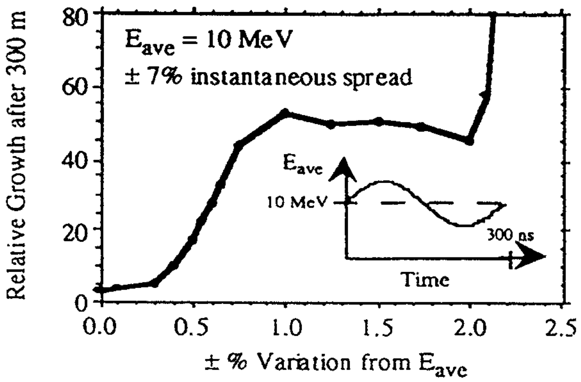

Figure 2. Simulation showing the effect of E_{ave} variation. The insert shows the E_{ave} profile over the pulse.

IV. RADIAL DEFOCUSING

2D numerical simulations carried out with the RKS2 code have shown that when the phase velocity, v_{ph}, of the operating mode (TM_{01}) in a TWS extraction cavity is different from the speed of light (detuned cavity) the beam experiences a radial kick from the field much larger than the case when v_{ph} is equal to c (non-detuned cavity). The radial kick is significantly larger than what is predicted by the Panofsky-Wenzel (P-W) theorem [7] for a closed cavity. The radial kick, if true and uncompensated, will cause the loss of the beam as it traverses the extended RK, as shown in Figure 3. Preliminary analytical and numerical studies have been performed in order to identify and understand the source(s) of the above discrepency. Two questions need to be answered: (1) How reliable the simulation results are; and (2) How good the resonant cavity model, which the RKS2 code is based upon is in describing the radial focusing force.

In developing the analytical model, we assumed a single dominant traveling-wave mode (TM_{01}) in a cylindrically symmetric cavity. Then, using the impedance of the mode, it can be shown that the radial force acting on an electron traveling in a cavity is $(e/2\gamma^2)E_r$ for a non-detuned cavity and $e(1-v_{ph}/c)E_r$ for a detuned cavity (where E_r is the radial electric field and γ is the relativistic factor). This indicates immediately that the radial force increases by two order of magnitude when the cavity is detuned as compared to the synchronism case (In our present RK design, $\gamma = 20.6$ and $|1-v_{ph}/c| \approx 0.3$).

The corresponding radial momentum change of the particle can be calculated in a first order approximation by integrating the force over the length of the cavity, assuming that the electron's trajectory in the cavity is not affected by the field. For the case where $v_{ph} \neq c$ the formula is given as the following

$$\Delta p_x = \left(\frac{e\xi}{c}\right) x \cdot \sin\left[\left(1 - \frac{v_{ph}}{c}\right)\frac{\phi}{2}\right] \sin\left[\left(1 - \frac{v_{ph}}{c}\right)\frac{\phi}{2} - \omega t_o\right] \quad (3)$$

where ϕ is the phase advance of the wave field per cell, ξ is the amplitude of the electric field on axis, x is the transverse position of the electron with respect to the axis and ωt_o is the phase of the electron at the entrance of the cavity with respect to the field.

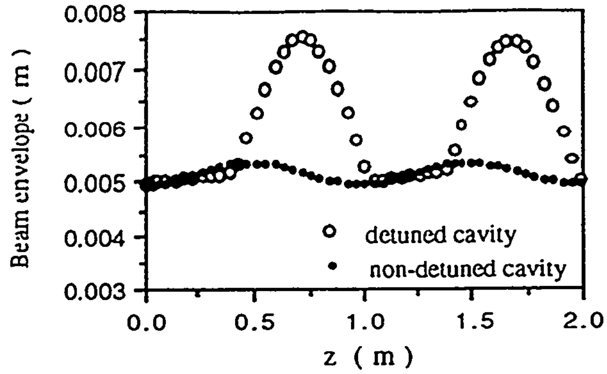

Figure 3 Beam envelopes in a 2-m reacceleration section after inductively detuned and non-detuned cavities.

From eq. (3) we can see that the increase of the radial momentum of the electron due to the wave field has the following features: i) a sinusoidal dependence on the detuning of the cavity (measured by v_{ph} and ϕ); ii) a sinusoidal dependence on the longitudinal position of the electron in the bunch ωt_o; iii) a linear increase with the distance of the particle from the axis.

The above observations agree with the numerical results from RKS2 to within 10% (as shown in Figure 4).

The resonant cavity model the RKS2 code based on has been used rather successfully for power balance for TM_{01} and BBU study for a dominant dipole mode. However, the validity of the model for the radial focusing force of the field has never been tested.

V. CONCLUSIONS

We have demonstrated in 1-D numerical studies the modulation and transport of the induction beam through the RK. Approximately 360 MW of rf (11.424 GHz) power was generated in each of 150 output structures. Longitudinal stability was accomplished by detuning the traveling-wave output structures to compensate for space charge effects and energy spread. Transverse stability required damping of higher order modes in resonant structures, Landau damping, and the "Betatron Node Scheme."

2-D numerical studies are required to study issues related to beam emittance, transverse space charge, and radial focusing. Initial 2-D studies show that the beam experiences a large radial momentum change during transit of the detuned output structures, which does not agree with the P-W theorem. Additional analytical and numerical studies tend to suggest that the discrepency could be caused by the less rigorous treatment in the RKS2 code of the boundary condition that affect the transverse dynamics. So, the effect might not be as serious as the code predict. But,

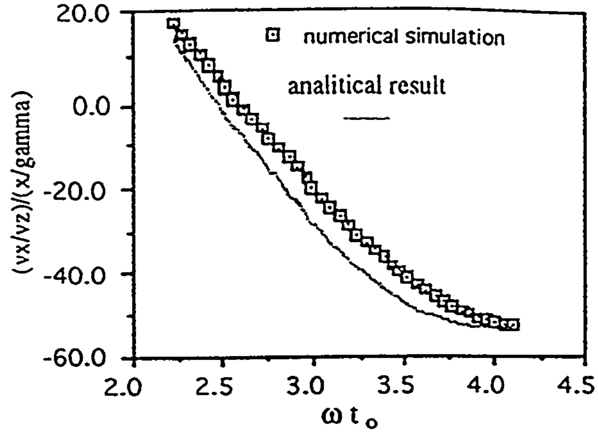

Figure 4. Normalized transverse phase space vs. phase after one inductively detuned cavity (v_{ph} = 1.33c), analytical and numerical results.

if it is, there are available several compensating schemes which can be explored:

1) Use exterior cavities that are coupled to the detuned TWSs to compensate the radial defocusing;

2) Use non-detuned TWSs as extraction cavities with the longitudinal bunching being provided by idler cavities positioned before and after each of the TWS.

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