CONCEPTUAL ANALYSIS OF A COMPACT HIGH EFFICIENCY KLYSTRON

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Abstract

Traditional klystron efficiencies are limited by the output electron beam harmonic current and energy spread. Increasing the amount of harmonic current produced in the klystron requires increasing the velocity bunching in the input cavity. Additional cavities may be used to improve the bunching, however they do so at additional cost and space requirements for the klystron. Moreover, at higher currents space charge counteracts this velocity bunching reducing the amount of harmonic current that can be produced. Our concept resolves these challenges by employing a new type of high-efficiency, multi-beam klystron. Our design consists of a single two-frequency input cavity, a wiggler, and an output cavity. The two-frequency input cavity approximates a linear function in time thereby increasing the harmonic content of the beam, while the wiggler provides strong longitudinal focusing to mitigate the effects of space charge. In this paper we provide the theoretical foundation for our design and present initial numerical calculations showing improved bunching from the harmonic mode and the wiggler.

INTRODUCTION

In a klystron the efficiency is determined by how much DC current can be converted into current at the fundamental frequency of the output cavity (harmonic current). The effectiveness of this bunching is usually limited by nonlinear velocity bunching and space-charge forces [1, 2]. Two common methods for improving klystron efficiency are the core oscillation method (COM) and the Bunch-Align-Compress (BAC) methods [3–5]. The COM method uses gain cavities spaced at the bunch oscillation length in order to allow the anti-bunching particles to smoothly merge into the central bunch. This has been shown in simulation to achieve efficiencies of up to 90%. There is a significant space cost however in that these klystrons tend to be between 50% and 100% larger than their more traditional counterparts. The BAC method has recently been a popular alternative to the COM method due to its more compact design, [6, 7]. Here cavities are strung together in triplets in order to more efficiently focus the beam longitudinally. These designs have shown a improvement in efficiency on the same scale as the COM designs however only a 10% to 20% increase in size compared to traditional klystrons. In both of these cases however the klystron design requires a number of bunching cavities and they tend to be large compared to other sources such as magnetrons.

Our paper explores a novel klystron circuit that enables a compact, high efficiency, source to be produced at low cost. We utilize two-frequency bunching combined with wiggler focusing to increase the harmonic current output while simultaneously decreasing the overall footprint.

THEORETICAL PRINCIPLES

High-efficiency RF amplifiers, such as klystrons, require harmonic current amplitudes I_1 about equal to the average input current I_0. The efficiency of a klystron is roughly proportional to $I_1/2$, therefore a tube with 100% harmonic current is approximately 50% efficient. To reach 80% efficiency, a harmonic current of about 160% is required. Starting with small-signal modulation of the electron beam from an input cavity, a klystron uses a series of gain cavities and large-signal cavities to increase the beam's harmonic current. These cavities are all powered parasitically by the beam. An output cavity at the location of peak harmonic current is phased to decelerate the bunch and, produces the klystron's output power. Ballistic bunching in a two cavity klystron can be described analytically by propagating a velocity modulated beam over some finite distance.

The velocity of a particle that exits the two frequency input cavity as a function of time can be described in the zero current limit by Eq. (1),

$$v_{\mathrm{exit}} = v_0\left(1 + X\sin(\omega t_0) + Y\sin(2\omega t_0)\right). \qquad (1)$$

Here $X{=}TV^{\mathrm{f}}_{\mathrm{gap}}e/(mc^2\gamma^3\beta^2)$ and $Y{=}TV^{\mathrm{h}}_{\mathrm{gap}}e/(mc^2\gamma^3\beta^2)$. The time of flight from the cavity to some position z can be approximated by $t-t_0 = z/v_0(1-X\sin(\omega t_0)-Y\sin(2\omega t_0))$. Note that here we have both the fundamental, ω, and the second harmonic, 2ω, affecting the beam velocity modulation. We can then calculate the harmonic current at z by decomposing the beam into Fourier harmonics,

$$I(t) = I_0 + \sum_{n=1}^{\infty} a_n\cos(n(\omega t-\theta)) + b_n\sin(n(\omega t-\theta)). \quad (2)$$

Here a_n and b_n are the Fourier coefficients and θ represents a phase shift characterized by the bulk propagation time of the beam $\omega z/v_0$. The magnitude of the a_1 term gives a first approximation of how efficient the klystron will be. When solving for the Fourier coefficients it is useful to define the instantaneous current as $I(t) = I_0 dt_0/dt$, which transforms the integrals of a_n and b_n to be over t_0. Then using a change of variables, we can compute the a_n terms by solving Eq. (3),

$$a_n = \frac{I_0}{\pi}\int_{-\pi}^{\pi}\cos(n(\phi - X\sin(\phi) - Y\sin(2\phi)))d\phi\,. \quad (3)$$

Noticing that b_n is zero everywhere, we can now write the harmonic current at some position z after the bunching cavity by numerically integration Eq. (3). This allows us to estimate the efficiency of a two cavity klystron using harmonic bunching. Figure 1 shows the zero current efficiency as a function of the strength of the harmonic and fundamental frequencies in the input cavity. Without additional bunching cavities we can achieve close to 75% efficiency using the combination of fundamental and first harmonic fields in the input cavity.

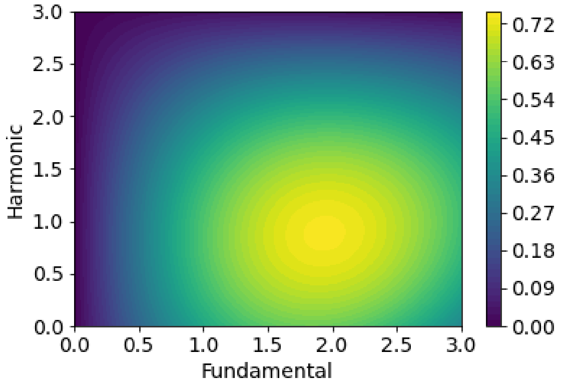

Figure 1: Estimated efficiency of a klystron as a function of the fundamental and harmonic input strengths.

For a beam with a velocity modulation, we can produce additional bunching by coupling the transverse and longitudinal dynamics through a magnetic field. Wigglers have previously been used for focusing in klystrons [8, 9], we take a similar approach in addition to exploring more exotic configurations such as tapered wigglers and solenoids. An added benefit of the wiggler is that the inclusion of a curved path shortens the physical distance needed for velocity bunching. A 1-D example of wiggler enhanced bunching in a klystron is shown in Fig. 2.

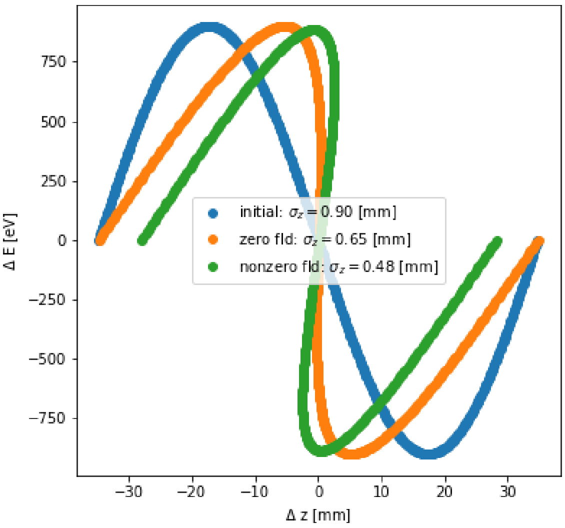

Figure 2: Longitudinal phase space for a beam in a klystron with and without wiggler enhanced focusing.

Here we can see a significant reduction in the bunch length when the beam passes through the wiggler. Thus the effective harmonic current achieved is higher than the simple drift case.

CONCEPTUAL CAVITY DESIGN

We have completed a conceptual design for the two frequency RF cavity using SUPERFISH. The cavity structure follows the typical two frequency structure used in similar studies. The design is optimized to excite two harmonic modes that have the same longitudional field profile. Figure 3 shows the result of a simple SUPERFISH simulation for a two frequency bunching cavity that can operate at 1.3 GHz and 2.6 GHz in the TM010 mode. The longitudinal field profiles for these modes are almost identical as is shown in Fig. 4.

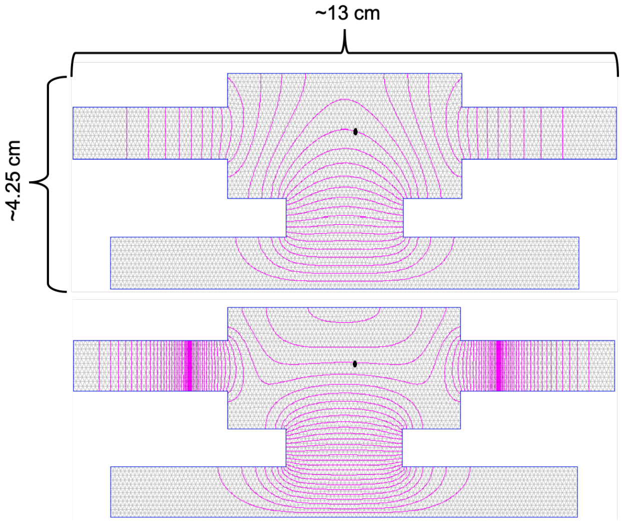

Figure 3: Superfish simulation of two frequency cavity operating at 1.3 GHz (top) and 2.6 GHz (bottom).

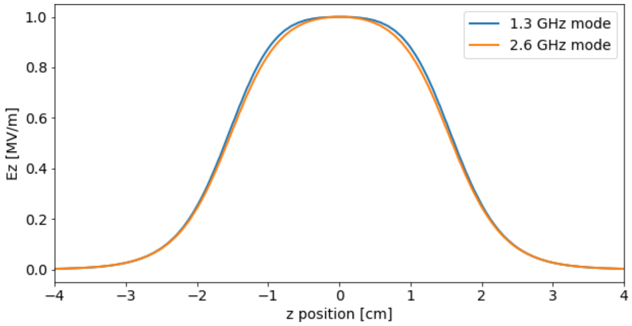

Figure 4: Superfish simulation of two frequency cavity operating at 1.3 GHz and 2.6 GHz axis field profiles for the two modes.

FUTURE WORK

With a solid foundation in theory we plan to expand this effort into a physics design including space-charge effects and realistic field maps for the cavity and the wiggler magnet. We will also design a proper magnetic focusing channel to ensure beam confinement. We anticipate this principle could achieve better than 80% efficiency while maintaining a compact geometry. Our first order calculations indicate that harmonic bunching along will increase the efficiency to greater than 70%. The addition of wiggler focusing lowers the bunch length by 25% which we expect will increase the efficiency to greater than 80% without the addition of a depressed collector.

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