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Publication Date

2000-08-01

The RTA Betatron-Node Experiment: Limiting Cumulative BBU Growth In A Linear Periodic System

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Abstract

The successful operation of a Two-Beam accelerator based on extended relativistic klystrons hinges upon decreasing the cumulative dipole BBU growth from an exponential to a more manageable linear growth rate. We describe the theoretical scheme to achieve this, and a new experiment to test this concept. The experiment utilizes a 1-MeV, 600-Amp, 200-ns electron beam and a short beamline of periodically-spaced rf dipole-mode pillbox cavities and solenoid magnets for transport. Descriptions of the beamline are presented, followed by theoretical studies of the beam transport and dipole-mode growth.

1 INTRODUCTION

A Lawrence Livermore National Laboratory (LLNL) and Lawrence Berkeley National Laboratory (LBNL) collaboration is studying the application of induction accelerator technology to the generation of microwave power. We refer to this scheme of power generation as the Relativistic Klystron Two-Beam Accelerator (RK-TBA) [1]. This scheme is considered a TBA approach as the extraction of microwave power is distributed along a drive beam parallel to the high-energy rf linear accelerator. The RK designation indicates that the power is generated by the interaction of the relativistic modulated drive beam with resonant structures similar to those used in a conventional klystron.

The primary advantage of TBA concepts is that the conversion of drive beam power to microwave power can be highly efficient (>90%). This efficiency is realized by distributing the power extraction over an extended length. The interest in RK-TBA's is that induction accelerators are efficient at producing very high power electron beams. Present induction accelerators operate at currents of several kilo-amperes and accelerate the beam to 10's of MeV for beam power of 100's GW [2]. The induction accelerator can realize improved efficiency at converting wall plug power into beam power by replacing the standard electromagnet solenoids for beam transport with permanent magnets. Even higher efficiency can be attained if the induction cells are used as high-voltage step up transformers driven by a relative low voltage (∼20 kV) pulsed power system. Present designs of a RK-TBA predict efficiency of about 40% in conversion of wall plug power into beam power [3], or a total wall plug to microwave power efficiency of about 36%. The main section of an RK where the microwave power is generated is comprised of many repeating modules as illustrated in Figure 1. Within each module, the induction cells replace the energy extracted from the electron beam by the microwave output structure. The efficiency of this process — extraction and reacceleration — is nearly 100%. Not shown in Figure 1 are the beam generation and modulation sections and the final beam dump. Fixed energy losses in those processes have to be included in calculating the total beam energy to microwave conversion efficiency. Thus, it is imperative that the RK have many of the efficient extraction and reacceleration cycles to reduce the relative value of fixed losses with respect to the total energy transferred to the beam.

Several proof-of-concept experiments have been performed to demonstrate the viability of the RK-TBA concept. These experiments have shown the generation of collider-scale drive beam in induction linacs, production of high-quality, high-power microwaves from standing- and traveling-wave structures driven by induction accelerator beams, and multiple reacceleration and extraction cycles [4, 5]. As will be described below, we are continuing to perform experiments to study specific physics and technology issues while constructing a prototype relativistic klystron.

2 BEAM DYNAMICS ISSUES

The ultimate efficiency of a RK is determined by the induction beam dynamics i.e. the number of extraction structures that the beam can transit. We have identified three critical areas of beam dynamics that must be understood. The first involves maintaining the longitudinal modulation of the beam or "rf bucket" structure. In the drifts between output structures, space charge forces will cause the beam to lengthen in phase space, i.e., "debunch". If this effect is not corrected, the rf current (Fourier component of the beam at the modulation frequency) will decrease resulting in a decrease in the microwave power that can be extracted. Inductively detuning the output structures, similar to the penultimate cavity in conventional klystrons, can counter the space charge forces. The requirement for long-term longitudinal stability is reestablishing the initial longitudinal charge distribution at the end of a synchrotron period. Computer simulations have shown that with proper detuning, the rf current can be maintained over the 150 output structures envisioned for a full scale RK-TBA [6].

The other issues involve transverse instabilities. The beam will excite dipole modes in the induction cell accelerating gaps as well as in the resonant output structures. The induction cell accelerating gaps can be severely damped with rf absorbers for all resonant modes since the applied voltage pulse is quasi-static compared to the resonant frequencies. In addition, the natural energy spread over the rf bucket contributes to phase mixed, or Landau, damping. The combination of rf absorbers and energy spread is expected to maintain the transverse instability due to the dipole modes in the accelerating gaps at acceptable levels.

The resonant output structures present a more difficult transverse instability issue. The fundamental mode must couple sufficiently with the beam to extract the required energy. Various techniques exist to damp higher order modes in both output and accelerating structures. However, the permanent magnet focusing system envisioned for an RK-TBA allows the application of a new technique that we refer to as the *Betatron Node* Scheme.

Transverse beam instability theory is well developed and the exponential growth predicted is supported by experiment. However, the standard theoretical approach assumes that the discrete cavities interacting with the beam are closely spaced compared to the betatron wavelength due to the focusing system. Our design for an RK-TBA system requires strong focusing to maintain the required beam radius and a constant average energy over each extraction/reacceleration cycle. This combination leads to spacing between output structures of one betatron wavelength and the basic assumption of the standard theoretical approach does not hold.

An alternative approach to studying the transverse instability uses transfer matrices [7]. Assuming a monoenergetic beam and a thin cavity, Equations (1) through (3) indicate the salient parts of this theory. Equation (1) represents the transverse momentum change an electron receives passing through the cavity. *R* is an integral operator that accounts for the part of the beam that has already passed through the cavity. The first matrix on the RHS of Equation (2) is then the transfer matrix for the beam going through the cavity. For a sufficiently thin cavity, the transverse position does not change. Only the momentum is affected. The second matrix represents the betatron motion of the electrons between cells where θ is the phase advance. Thus, Equation (2) advances the position and momentum of electrons from the exit of on cavity to the exit of the following cavity. By repeatedly multiplying the two transfer matrices, the position and momentum at the exit of any cavity can be related to the initial conditions. For the situation where θ is constant for all sections and $\theta \ll 1$, the series of matrix multiplications can be shown to yield the same expected exponential growth as the more standard approach.

$$\Delta p_\perp = R \cdot x \tag{1}$$

$$\begin{bmatrix} x \\ p_\perp \end{bmatrix}_{n+1_{exit}} = \begin{bmatrix} 1 & 0 \\ R & 1 \end{bmatrix} \begin{bmatrix} \cos\theta & \frac{\sin\theta}{\omega} \\ \omega\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} x \\ p_\perp \end{bmatrix}_{n_{exit}} \tag{2}$$

For the case where $\theta = 2\pi$ (or any integral multiple of π), the matrix multiplication is greatly simplified. The betatron motion returns the electrons to the original transverse position and momentum (oppositely directed for odd multiples of π). The multiplication involves only the matrix describing the effect of the cavity, and, as shown in Equation (3), this leads to a linear growth in the transverse instability

$$\begin{aligned} \begin{bmatrix} x \\ p_\perp \end{bmatrix}_{n+1_{exit}} &= \\ = \begin{bmatrix} 1 & 0 \\ R & 1 \end{bmatrix}^n \begin{bmatrix} x \\ p_\perp \end{bmatrix}_{(n=1)_{exit}} & \\ = \begin{bmatrix} 1 & 0 \\ nR & 1 \end{bmatrix} \begin{bmatrix} x \\ p_\perp \end{bmatrix}_{(n=1)_{exit}} & \end{aligned} \tag{3}$$

There are many non-ideal factors in a realistic accelerator including cavities of finite thickness and variation in phase advance due to energy and/or focusing errors. Parameter studies through computer simulations indicate that the transverse instability is significantly reduced for systems with reasonable variations in parameters. We intend to experimentally test the validity and robustness of the Betatron Node Scheme.

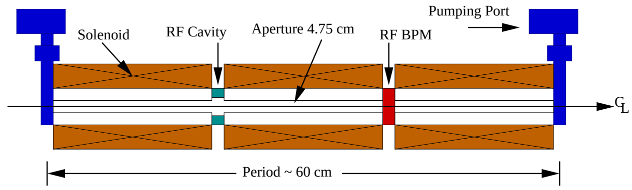

Figure 1: Minimum beamline configuration.

3 BETATRON NODE SCHEME EXPERIMENT

The basic elements involved in a test of the Betatron Node Scheme are: a set of devices that generate a localized transverse impedance, a tunable focusing and transport system, and diagnostics to measure the BBU mode signal on the beam as a function of time and distance along the beamline. A schematic for a possible beamline is shown in Figure 1.

The localized impedances are generated in simple pillbox cavities, tuned so that the TM_{110} mode frequency matches the modulation of the beam; a series of solenoid magnets provide tunable focusing; and rf BPMs placed between cavities provide a means of collecting the dipole mode signal carried by the beam. We have built several sections of this beamline, using off-the-shelf components wherever possible. Each section is one betatron wavelength long and is comprised of one pillbox cavity, a pumping port, a diagnostic, and three solenoids. The rf cavities have a simple pillbox design, with a dielectric insert (Alumina 99.5%, $\epsilon \approx 9$) to adjust the mode frequency. The dipole mode resonates at ~5.2 GHz, with a wall-loaded Q-value of ~100 and a normalized transverse impedance $\left[\frac{Z_\perp}{Q}\right]$ ~6.5Ω.

Computer simulations of the increase in power measured by the rf diagnostics at the dipole mode frequency

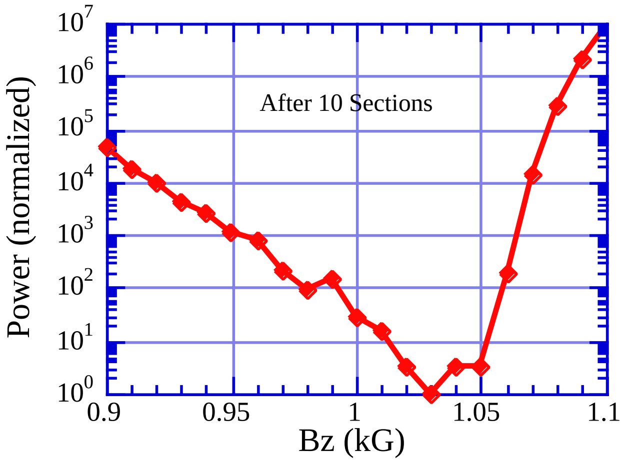

Figure 2: Dipole mode power vs. solenoidal field (phase advance).

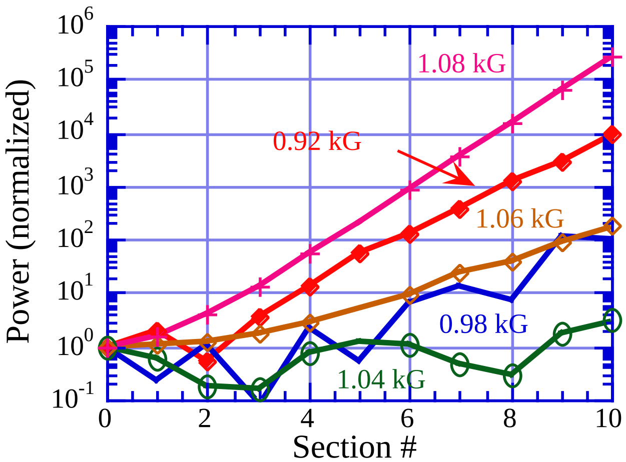

Figure 3: Dipole mode power vs. length for varying solenoid fields, displaying linear and exponential growth regimes.

are shown in Figures 2 and 3.

Variations of $\pm 10\%$ in the solenoidal field (betatron phase advance) from the optimum should produce several orders of magnitude increase in measured mode power after only a few sections. The graphs indicate the maximum power expected during the main body of the beam ("flat top"). The temporal power variation during the pulse (not shown) is predicted to have different characteristics between under- and over-focused scenarios.

4 SUMMARY

The long-term goal of the RTA Facility is to build a prototype relativistic klystron that has all the major components required for a RK suitable for collider applications. The prototype would serve as a test bed for examining physics, engineering, and cost issues. The first major component, the 1-MeV, 600-A, induction electron gun, of the prototype has been completed and commissioned. Before continuing with the next section of the prototype, we intend to perform a series of beam dynamics experiments. In particular, we will demonstrate the effectiveness of the Betatron Node Scheme. We are also continuing to study and optimize collider designs based on the RK-TBA scheme.

5 ACKNOWLEDGMENTS

We thank Swapan Chattopadhyay, George Caporaso, Kem Robinson, and Simon Yu for their support and guidance. Dave Vanecek and Wayne Greenway provided invaluable mechanical engineering and technical services. John Corlett and Bob Rimmer designed the rf diagnostics. This work was performed under the auspices of the U.S. Department of Energy by University of California Lawrence Berkeley Livermore National Laboratory under contract No AC03-76SF00098 and Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

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