THE DISTRIBUTED BUNCH AMPLIFIER*

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Abstract

The Distributed Bunch Amplifier (DBA) is a high efficiency RF source that utilizes a phase locked deflecting cavity and output circuit to produce a synchronous beam-wave interaction. The DBA improves on the design of previous embodiments of this technology, such as the Gyrocon, by implementing a modern decoupled output circuit design and conical PPM beam focusing array in order to scale to higher frequencies and efficiency than previously demonstrated [1]. Presented is a proof-of-concept S-band, 2.856 GHz, device operating with a 60 kV, 8 Amp, electron beam. Each stage of the three-cavity decoupled output circuit is optimized based on complex amplitude and shunt impedance to achieve an electronic efficiency of greater than 90%. Initial numerical analysis of this design indicates that an overall operating efficiency of greater than 80% is feasible. Detailed simulated results of the S-band model and designs to scale this technology to higher power and frequency will be discussed.

INTRODUCTION

Linear beam tubes such as the Klystron have historically been used to drive industrial linear accelerators operating at (1-10 MeV). These systems, which can require high average power (0.1-1 MW), utilize commercially available designs that demonstrate a peak RF efficiency of approximately 60%. This limited efficiency is due, in part, to an intrinsic limitation of the electronic efficiency for this class of device.

Deflected beam devices are a well-developed technology that capable of operating with electronic efficiencies in excess of 90%. These sources, which included the Gyrocon and Magnicon, owe this exceptional operating characteristic to a phase synchronous beam that does not require longitudinal bunching [1–3]. Total efficiencies in the realm of 60-80 (%) have been demonstrated at low frequencies (0.2-0.4 GHz) and high average powers approaching 0.5 MW. Many of these devices, however, operate with high beam voltages between 200-1600 kV, which places prohibitively taxing design constraints on the output resonant structure.

The proposed distributed bunch amplifier (DBA) improves upon these devices by revamping the interaction circuit with a multi-cavity decoupled output network. This novel coupling mechanism, developed originally for the Distributed Coupling Accelerator, allows for a disseminated voltage across many cavities therein reducing both resistive loss and peak surface fields [4]. The device is also designed with a novel, conically shaped, PPM array to focus the drifting beam, enabling lower beam voltages and higher current operation.

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The DBA circuit is composed of a series of azimuthally symmetric cavities with elliptical lobe on either side of a conical beam path shown in Fig.1. Proper tuning of each lobe allows for nearly perfect cancellation of the transverse fields within the drift tube and produces a purely longitudinal component of the electric field on axis.

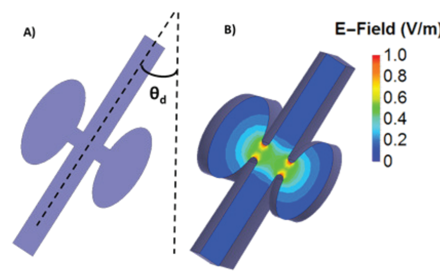

Figure 1: An image of (A) general cross section of a typical output cavity at angle θ_d as it relates to the deflection angle of the e-beam and (B) a contour plot of the electric field for the TM mode of operation.

Similar to preceding technology, these TM mode cavities are phase locked to the azimuthally traveling mode in the deflecting cavity providing perfect synchronism with the injected electron beam. The relative phase of each cavity in the decoupled array is tailored such that the beam experiences only a decelerating phase of the RF with minimal consideration for coupling and separation between them. The external coupling factors are optimized on the basis of shunt impedance to limit resistive losses and potential for RF breakdown.

Initial studies using a two-cavity output structure with an 8A, 60 kV, electron beam (shown in Fig.2) was evaluated in simulation using a single particle complex power balance algorithm in conjunction with eigen-solutions from the finite element code HFSSv.16. These preliminary results have validated that a single DBA unit is capable of achieving 500 kW output power with total efficiencies in excess of 80%. Translating this preliminary study into a working, high efficiency, device is dependent largely on careful design of the proposed output circuit and a low loss beam focusing system that is viable for 10-60 kV.

Extraction Network

The power combining system is designed to provide isolation between resonators by manipulating sections of the microwave network at a particular frequency and phase of

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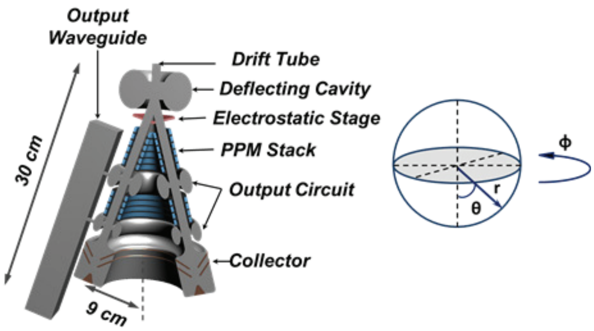

Figure 2: A 3-D CAD rendering of the DBA conceptual configuration at S-band.

which the device is known to operate. An analytic estimate of these conditions is attained using the sample network in Fig.3 consisting of two resonators (internal ports 4 and 8) and an open output port (external port 1).

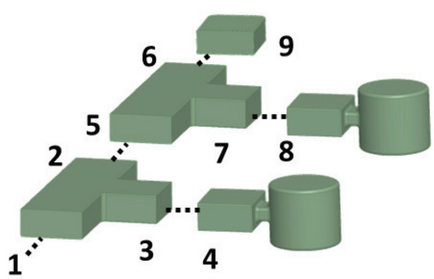

Figure 3: The 9-port (1 external) power extraction network featuring two isolated resonators at arbitrary frequency, phase, and power.

The full N-port power combiner is established by defining the scattering parameters of each subnetwork such that the full cascaded model maintains complete isolation between the resonator ports. These sub-circuits include a simple 3-port network in Eq.1 defined by the coupling and phase constants (θ and ϕ), a single port resonator defined by its unloaded Q (Q_0), resonant frequency (f_0) and coupling factor (β) in Eq.2, and a shorted arbitrary waveguide of length (L_0) shown in Eq.3.

$$S_A = \begin{pmatrix} \frac{-\cos(\theta_1)-e^{i\phi_1}}{2} & \frac{-\cos(\theta_1)+e^{i\phi_1}}{2} & \frac{\sin(\theta_1)}{\sqrt{2}} \\ \frac{-\cos(\theta_1)+e^{i\phi_1}}{2} & \frac{-\cos(\theta_1)-e^{i\phi_1}}{2} & \frac{\sin(\theta_1)}{\sqrt{2}} \\ \frac{\sin(\theta_1)}{\sqrt{2}} & \frac{\sin(\theta_1)}{\sqrt{2}} & cos(\theta_1) \end{pmatrix} \tag{1}$$

$$S_B = \frac{f^2 Q_0 - f_0^2 Q_0 + j f_0 f(\beta - 1)}{f^2 Q_0 - f_0^2 Q_0 - j f_0 f(\beta + 1)} \tag{2}$$

$$S_C = e^{-j2L_0} \tag{3}$$

Each scattering matrix is cascaded using a predefined (9x9) topology matrix and the resonator ports (4,8) are internally excited with proper amplitude and phase to generate the appropriate outgoing voltages (a_{1-9}) [5]. The resulting incoming voltages (b_{1-9}) are then used to define the constraints of the modeled network where isolation is provided by Eq.4.

$$\frac{b_8}{a_4} = \frac{b_4}{a_8} = 0 \tag{4}$$

Permanent Magnet Focusing

Low voltage deflecting beam devices require the use of an external focusing system to maintain proper transport of electron beam through the device. The use of a solenoid field, as with the Magnicon, not only increases the amount of power consumption ($5 - 10kW$) but also requires sufficient cooling thus increasing the size, weight, and cost of the overall device. An alternative to improve efficiency and mitigate complication is to implement a periodic permanent magnet (PPM) array exterior to the extraction network show in Fig.2. The conical geometry of the DBA drift tube closely resembles that of a planar configuration where the magnetic field does not maintain complete azimuthal symmetry about the circular beam. Implementation of these PPM configurations are often used in sheet beam devices such as TWTs and Klystrons where careful consideration must be given to the Diocotron instability and beam edge effects [6]. These effects in the DBA however, are not considered as deleterious due to the small aspect ratio of the deflected beam and low fill factor in the drift tube ($\sim 50\%$). The required Brillouin rms field on axis is thus approximated as through it were a cylindrically stacked array as shown in Eq.5, where (r_0) is the beam radius, (I_0) is the beam current and (u_0) is the beam velocity [7].

$$B_{axis} = \frac{2I_0 m}{\pi \epsilon_0 q u_0}(\frac{1}{r_0})^2 \tag{5}$$

The initial design of such a conical PPM array was generated using a staggered array of SmCo magnets whose positions were estimated numerically using the Amperian model from Eq.6 (where J x n is equivalent to the residual magnetization vector $\vec{M}$ for SmCo).

$$A = \frac{\mu_0}{4\pi}[\int\int_{r_0}^{r_1} \frac{\vec{J}X\vec{n}}{\mu_0|r-r'|} rdrd\theta - \int\int_{r_2}^{r_3} \frac{\vec{J}X\vec{n}}{\mu_0|r-r'|} rdrd\theta] \tag{6}$$

The resultant numerical design was then expanded to a array in Maxwell v.11 using SmCo disks separated by iron pole pieces. The field maps from the magnetostatic solver were then re-interpolated onto a grid in the particle in cell code MAGIC where a deflected beam was injected at its waist into the PPM focusing field. This preliminary design was able to demonstrate that such an array can propagate 25 A, 60 kV, beam with a 1 mm radius over the length of the device with negligible change in cross section or intercept with the wall.

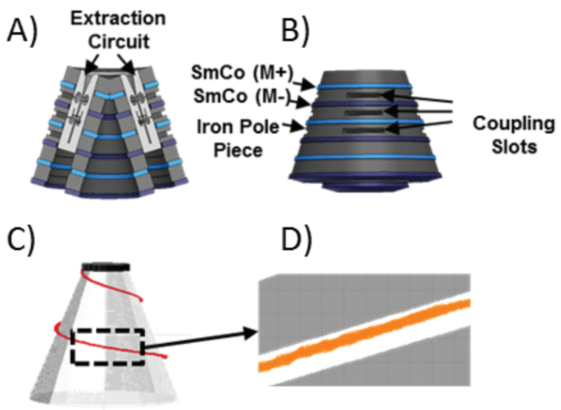

Figure 4: An image of (A) a cross section of the PPM array on the exterior of the extraction network, (B) the external rendering of the PPM array with coupling slots, (C) a MAGIC PIC simulated deflecting beam with PPM fields, and (D) an enlarged image of the beam inside the drift tube.

CONCLUSION

The DBA is a highly efficient, low voltage, device that is inherently phase-locked to its input signal. This natural synchronism lends itself to immediately to the prospect of an array of coherently locked amplifiers driven by a single source to achieve high output power [8]. The numerical studies presented in this article show proof of concept validation of a 8A, 60 kV, 2.856 GHz design, which may readily be scaled to higher frequency and peak power. Gains in the range of 20-25 dB should be achievable with proper implementation of novel RF deflecting structures with externally applied magnetostatic and electrostatic fields to augment the beams initial deflection [3]. Additional studies need to be performed to gather more information on space charge effects within the drift tube and its impact on energy spread and electronic efficiency. Full device simulations are currently under way using CST microwave studio.

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