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MAGNETIC FOCUSING ARCHITECTURE FOR A COMPACT ELECTRON BUNCHER *

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Abstract

We present a beam-focusing architecture using electromagnetic solenoids and permanent magnets for a novel compact electron beam buncher at *C*-band, under development for space-borne electron accelerators. Developing compact and efficient accelerator components has become desirable with renewed interest in using space-borne electron beams for ionospheric aurora research and for very low frequency wave generation for particle removal from the magnetosphere. An electron gun injects a direct-current (DC) electron beam, and the buncher modulates the beam into periodic bunches at a frequency of 5.7 GHz. A 5.7-GHz linear accelerator in the downstream will capture the bunched beam with minimal longitudinal acceptance mismatch. The beam bunching is achieved by three radiofrequency (RF) cavities. The buncher uses the electrostatic potential depression (EPD) method to shorten the structure length remarkably. We use a series of tunable permanent magnets to focus the beam through the buncher.

INTRODUCTION

Space-borne electron accelerators play a crucial role in space research and various applications. For instance, accelerators can inject a beam in the ionosphere and magnetosphere to probe and actively map them, to help us better understand the auroral activities [1]. Electron beams produced by space-borne accelerators can be used for radiation-belt remediation (RBR) [2], which helps protecting the lower-earth-orbit (LEO) satellites. A space weather event or a high-altitude nuclear explosion (HANE) will generate MeV-level electrons that become magnetically trapped in the Earth's magnetic field. Those energetic electrons pose a threat to the LEO satellites, significantly reducing their life span. The RBR mission will use low-frequency space plasma waves to scatter the trapped MeV-level electrons, causing them to precipitate into the Earth's atmosphere. One promising method of generating the desired space plasma waves is through the interaction between an electron beam, which is injected from a space-borne accelerator, and the space plasma. However, existing RF accelerator technology faces significant challenges, including electron beam loss during acceleration and excessive energy spread in the accelerated electron beam. There is also a need to make accelerator components more compact for *in-situ* space applications.

At Los Alamos National Laboratory (LANL), we are studying a compact and power-efficient electron beam buncher. The buncher converts the input DC beam into a bunch train at a repetition rate equal to the operating RF frequency of the accelerator in the downstream. Our buncher structure takes after the architecture of a klystron, which comprises one input RF cavity, followed by idler cavities. The buncher is meanwhile compact, benefiting from the electrostatic potential depression (EPD) technology [3], which is described as follows. In our buncher architecture, between two neighboring RF cavities, one section of the beam pipe is insulated and biased with a negative high voltage (HV). When a pre-bunched electron beam enters the negative-HV-biased beam pipe section (referred to as an EPD section), the majority of its kinetic energy is removed; however, the relative energy difference among the electrons is preserved. On the one hand, when the beam moves much slower in the EPD section, the ballistic bunching mechanism allows the bunching to become elevated over a short distance; on the other hand, the stronger nonlinear space charge effect provides a further boost for increasing the bunching level [4]. In the end, when the beam leaves the EPD section, it regains the original kinetic energy, with a much enhanced bunching level. Lastly, the re-acceleration process provides longitudinal cooling to the bunched beam, reducing the energy spread.

The cavities and the EPD sections use permanent magnets, instead of traditional electromagnetic solenoids, for beam focusing. Permanent magnets do not require power supplies, making them ideal for space missions.

DESIGN OVERVIEW

Figure 1 shows the longitudinal cross section of the electron beam buncher system. The system consists of an electron gun from Kimball Physics (EGG-3103) that produces a 10-keV 50-mA DC electron beam. The electron gun is placed concentrically inside the two solenoids. The first solenoid is placed over the cathode of the gun, providing a hundred-Gauss magnetic field on the cathode, which can reduce the beam scalloping inside the EPD sections and after the bunches are formed. The second solenoid is placed over the beam's output, allowing for tuning the initial beam focusing. Downstream of the gun is the buncher structure, which includes three RF cavities. The first cavity is the input cavity providing the initial modulation; the other two cavities are idler cavities, the function of which is identical to the idler cavities in a klystron. Following each RF cavity, there is an EPD section, the length and HV value of which are determined through beam dynamics simulations. Surrounding

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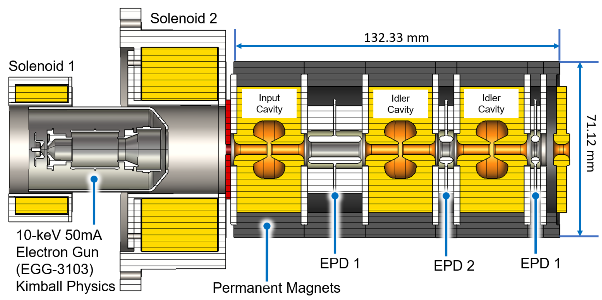

Figure 1: Cross-section view of the electron buncher.

the buncher, in the black color, is a set of seven permanent magnets for beam focusing.

The input cavity is powered by a milliwatt RF source that initiates the bunching process. The beam then travels into the first EPD section, which is biased with a -9 keV voltage. Upon entering the EPD section, the electron beam loses most of its kinetic energy (depressed), and the dynamics of the electrons become dominated by the space charge effects. Following the first EPD section is an idler cavity that operates in series with the other idler cavity. These cavities, assisted by the second and the third EPD sections, progressively increase the bunching level of the electron beam.

To focus the beam through the buncher, we use seven permanent magnets, one for each RF cavity and for EPD section, respectively, with an additional magnet at the end of the buncher to provide focusing at the output of the buncher.

SIMULATION RESULTS

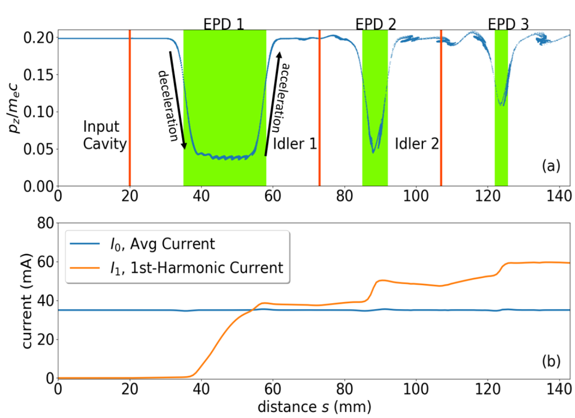

Figure 2: a) Electron beam longitudinal momentum evolution in the buncher. b) First harmonic current evolution as the bunching level increases.

Figure 2 shows the beam dynamics simulation results derived from the TUBE code [5]. The fields of the cavities and of the EPD sections were calculated in CST [6] 3D solvers and then imported into TUBE. The fields included the full range of the fringe fields. Figure 2a shows the variation of the longitudinal momentum p_z of the electron beam as it travels through the buncher structure, normalized by $m_e c$, where m_e is the electron mass, and c is the speed of light. The sections of the reduced momentum denote the locations of the EPD sections, where the majority of the kinetic energy of the electrons is removed. Figure 2b shows the evolution of the electron beam's first harmonic current I_1. The first harmonic current I_1 value represents the level of bunching achieved in the beam at the desired repetition rate of 5.7 GHz. The value of I_1 is the figure-of-merit of the buncher theoretical design. The entire calculation aims to maximize the I_1 value achieved in the buncher while ensuring a reasonable rms energy spread, e. g., below 5%. At the buncher exit, the I_1 is enhanced to I_1 = 59.7 mA = $1.68 I_0$, which is very significant.

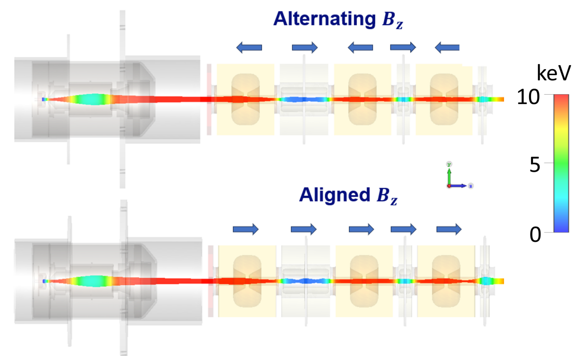

Figure 3: CST simulations of the electron trajectories using an alternating magnetic field orientation (top) and an aligned magnetic field orientation (bottom).

We used the CST Tracking Solver to fine-tune the magnetic fields for the electromagnetic solenoids and the permanent magnets. To simplify this simulation, no RF field was applied in the cavities. Figure 3 shows the electron trajectories for two cases of interest: permanent magnet focusing with an alternating magnetic field orientation, and with an aligned magnetic field orientation. The purpose of this compared study was to understand and then optimize the permanent magnet designs, to provide the desired magnetic field focusing while reducing the total weight of the permanent magnet required. For the alternating-field case, when compared with the aligned-field case, the magnetic fields provided by the permanent magnets surrounding the RF cavities were reversed. In both cases, the solenoid fields and the magnetic fields provided by the permanent magnets surrounding the EPD sections were always aligned. In Fig. 3, similar beam focusing was achieved, in the two cases of the magnetic field orientations.

Figure 4 shows the on-axis magnetic field profiles in the buncher, for the alternating and the aligned cases. Taking the average magnetic field magnitude along the buncher, we found that the alternating field case requires approximately 27.5% less field to produce the same amount of focusing as the aligned field case, which is significant. This is because the alternating field orientation allows for constructive addition of the magnetic fields provided by neighboring permanent magnets.

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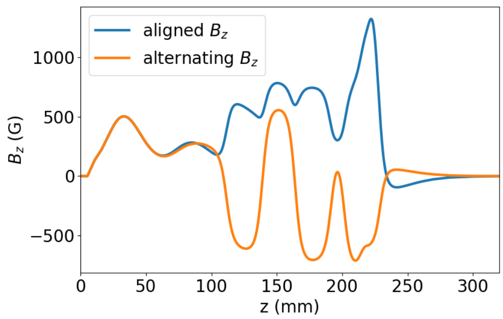

Figure 4: Focusing Magnetic field profiles along the axial component of the buncher for the alternating and the aligned magnetic orientations.

NOVEL PERMANENT MAGNET DESIGN

The permanent magnets used in the buncher study referred to research results produced at SLAC [7], as illustrated in Fig. 5, where eight pillar-shaped permanent magnets have been magnetized to a remanence of $B_r = 1$ T in the longitudinal direction, sandwiched between 1006-steel pole pieces. The highlight of this permanent magnet design is that it allows continuous tuning the on-axis magnetic field. Coarse adjustment of the on-axis magnetic field is through assigning a different number of the permanent magnets. Fine tuning is realized by changing the radial position of the permanent magnets. In Fig. 6, the on-axis peak magnetic field is plotted as a function of the radial position of the permanent magnet pieces. The configuration shown in Fig. 5 corresponds to a radial position of 28 mm in Fig. 6. From Fig. 6, it can be seen that the up-tuning is limited, if the permanent magnet pieces are moved radially inward; however, satisfactory down-tuning is realized by pushing the pieces radially outward, when the longitudinal end faces of the permanent magnet pieces are partially touching the pole pieces.

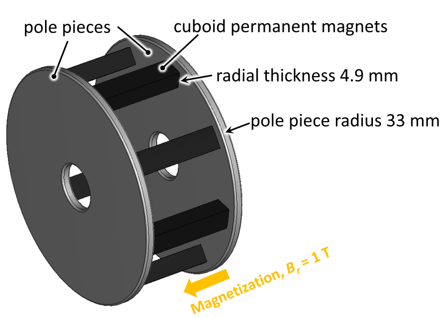

Figure 5: New permanent magnet design, which allows for the magnetic field to be continuously tuned.

CONCLUSION

This paper presents a power-efficient compact electron beam buncher architecture that is used for preserving direct-current (DC) electron gun beam charge for acceleration in an RF accelerator. The key technology involved is using the electrostatic potential depression (EPD) sections.

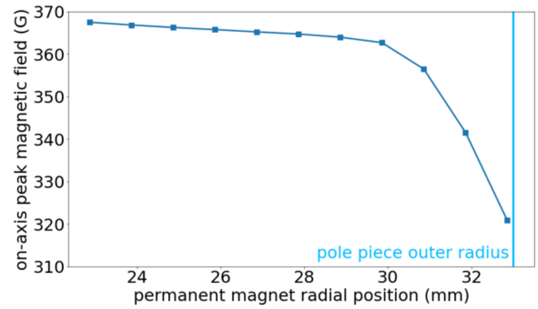

Figure 6: Tuning the on-axis magnetic field by adjusting the radial location of the permanent magnet pieces.

We present the results from fine-tuning a permanent magnet beam focusing structure for the buncher, with the on-axis magnetic fields of the permanent magnets arranged in an alternating and an aligned orientation. Our simulation results showed that alternating the magnetic field orientations between neighboring permanent magnets will lead to a significant reduction in the required on-axis field strength by each permanent magnet, which, in turn, lead to less remanence required or a reduced total weight of the permanent magnets.

We also present a new permanent magnet structure design that allows continours tuning of the magnetic field on the beam axis.

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