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COMPACT ELECTRON BUNCHER WITH TUNABLE PERMANENT MAGNET FOCUSING*

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Abstract

We present a compact electron buncher that uses a permanent magnet setup for beam focusing. The buncher modulates the input direct-current beam into 5.7-GHz bunch train. The buncher consists of two radiofrequency (RF) cavities. Immediately downstream of each RF cavity, there is an electrostatic potential depression (EPD) section. An EPD section in an electrically insulated beam pipe biased with a negative high voltage. The EPD method remarkably shortens the buncher structure by rapidly forming the bunch train. Each of the RF cavities and the EPD sections uses an individual set of rectangular permanent magnets, arranged in a circular array, which provide a solenoid-like focusing field. The polarity of the magnets is configured to form an alternating on-axis magnetic field orientation for minimizing the total weight. Coarse adjustment of the magnetic field is achieved by adding or removing permanent magnet rectangles. For fine adjustments, the rectangles are moved evenly in the radial direction. We show simulation results of the buncher performance and the tunable magnetic focusing. Initial experimental results are also reported.

INTRODUCTION

Accelerators deployed in space are used to advance space science and support a range of operational missions. For example, injecting electron beams into the Earth ionosphere and magnetosphere enables active probing and mapping of the space plasma, deepening our understanding of auroral phenomena [1]. Electron beams can also generate very-low-frequency (VLF) plasma waves in the Van Allen belts, which interact with and remediate high-energy electrons which pose a threat to low-Earth-orbit (LEO) satellites [2]. Large fluxes of such electrons arise after extreme space-weather events or high-altitude nuclear explosions (HANEs); once trapped in the Earth magnetic field, they can reduce the longevity of satellites. One mitigation strategy is to scatter these electrons with VLF waves, forcing them to precipitate into the Earth atmosphere. A promising driver for these waves is beam–plasma interaction from space-based electron accelerators, yet this approach still faces significant hurdles: minimizing beam loss, limiting energy spread, and designing compact, space-qualified accelerator systems for in-situ operation.

In this paper we present design and simulation results for a compact, power-efficient C-band (5.712 GHz) electron beam buncher, extending the work we reported at the 2024 International Particle Accelerator Conference (IPAC) [3]. The buncher converts an input, direct-current (DC) beam into a train of bunches at a repetition rate matched to the RF frequency of the accelerator in the downstream. The buncher adopts a klystron-inspired layout: a driven, input RF cavity is followed by an idler cavity, while the overall length is minimized with the electrostatic potential-depression (EPD) technology [4].

Moreover, we have introduced a continuously tunable permanent-magnet focusing scheme for the electron beam buncher. Rectangular bar magnets are mounted azimuthally and concentrically around each cavity and EPD section. Low-carbon steel pole pieces between the sections guide the magnetic flux to the paraxial region to provide a solenoid-like magnetic field distribution for beam focusing. For compact accelerator applications, such as space missions, permanent magnets are intrinsically advantageous, because they do not consume power, and thus no power supplies are required. In our permanent magnet assembly, the continuous tuning is achieved through a combination of coarse and fine tuning mechanisms.

ELECTRON BUNCHER DESIGN

Figure 1 shows the longitudinal cross section of the electron beam buncher system. The system incorporates an electron gun (model EGG-3103, Kimball Physics) that produces a 10-keV, 50-mA DC electron beam. Solenoid 1 provides magnetic field (400–500 Gauss) for the cathode for the purpose of reducing the beam scalloping when the bunches are developed. The second solenoid provides the initial focusing for the beam to be injected into the buncher structure.

The buncher has four sections, and it is a hybrid circuit involving both the RF and the high voltage (HV) components. The circuit is assembled using a clamping method, onto the 304 stainless steel mounting plate. Surrounding each section are the rectangular permanent magnet segments whose position is tunable, which are addressed in the next section. Figure 2 shows an external view of the complete buncher assembly. The buncher measures 121.84-mm in length.

The input RF cavity receives a fraction of 1 W of 5.712-GHz RF power from the source, and provides the initial bunching of the input, DC electron beam. The RF power is coupled into the cavity through a dedicated port using a small magnetic loop coupler.

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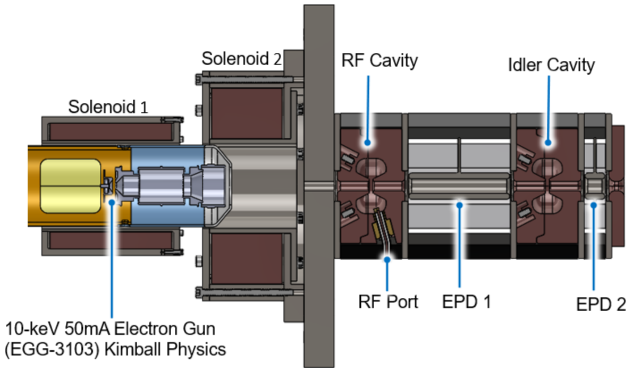

Figure 1: Half section view of the 5.712-GHz electron buncher system.

The pre-bunched beam enters the first EPD section, which is insulated from the metallic buncher body and a negative HV (−8.5 kV) is applied. The 10-keV beam is significantly slowed down to allow bunching to develop rapidly over a short distance. At the exit, the beam is re-accelerated to 10 keV. We originally proposed to use Macor spacers for the insulation, and now we are considering an alternative method, using vacuum-compatible epoxy potting for providing the mechanical support as well as insulation.

The idler cavity operates at 5.720 GHz, which is above the buncher operating frequency of 5.712 GHz. The inductive tuning allows the cavity to decelerate the head of the bunch and accelerate the tail of the bunch, enhancing the charge concentration towards the center of the electron bunch.

The last section is the second EPD section which operates at −8.3 kV. It provided the final boost in the bunching level of the electron beam, before the 10-keV electron beam is injected into the RF accelerator in the downstream.

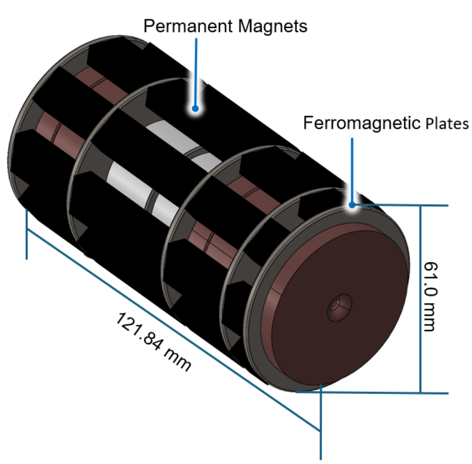

Figure 2: Rendering of the full electron buncher design.

PERMANENT MAGNET FOCUSING

Continuously tunable permanent magnet assembly is used for each section of the electron beam buncher circuit, as shown in Fig. 2. The permanent magnet rectangles of each

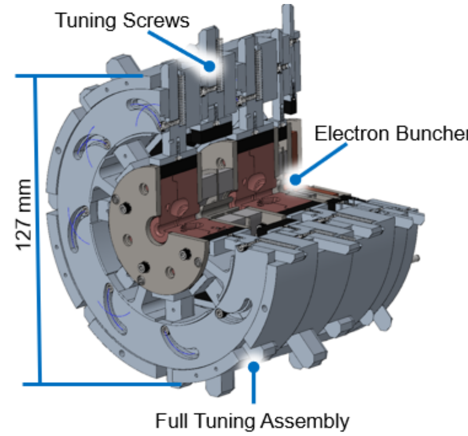

Figure 3: Mechanical design of the buncher structure with the permanent magnet position tuning mechanism included.

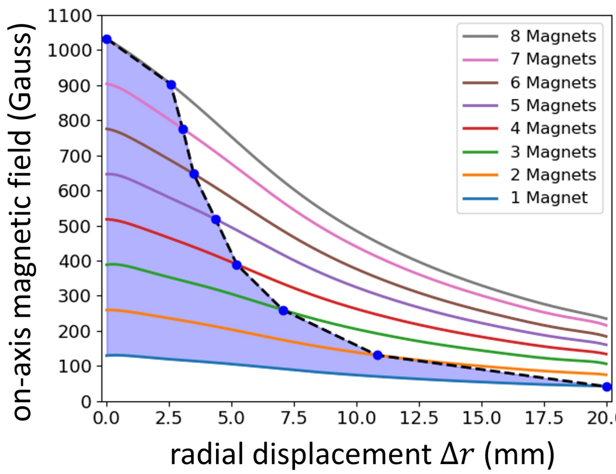

Figure 4: Principle of continuous tuning of the magnetic field on the beam axis. Separate lines represent different numbers of the permanent magnet rectangles used. Field strength variation of each line is enabled by adjusting the radial position of all magnets in one section.

section are moved in the radial direction simultaneously; the radial position of the magnets for each individual section can be adjusted separately. The mechanical design of the entire buncher circuit with the permanent magnet position tuning mechanism included is shown in Fig. 3. On the beam axis, the magnetic field provided by the permanent magnet assembly in each section is in alternating directions. This magnetic field alignment design saves the total weight of the permanent magnets while providing the equivalent electron beam focusing.

The permanent magnets are made of samarium-cobalt (SmCo), plated with nickel to minimize outgassing in a vacuum environment. The remanent flux is 1 T, parallel to the axial direction. For the cavity sections, this assembly can provide a peak axial magnetic field up to 1.1 kG. The assembly was studied using the CST Magnetostatic solver, and the continuity of the tuning of the magnetic field strength on the beam axis was confirmed.

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As shown in Fig. 4, the solenoid-like magnetic field distribution in the paraxial region is continuously tunable due to the combined mechanisms of coarse and fine tuning. The coarse tuning is provided by varying the number of permanent rectangles used (separate plot lines in Fig. 4); the fine tuning is by tuning the radial position of the permanent magnet rectangles (adjusting the radial displacement Δr of the magnets as shown in Fig. 4).

Furthermore, it was also discovered in the simulations that no matter how many permanent magnet rectangles were used, from one piece to all eight pieces, the azimuthal uniformity of the longitudinal magnetic field in the paraxial region was always very well preserved. The maximal normalized non-uniformity was always less than 0.1%.

BEAM BUNCHING SIMULATIONS

Electron beam bunching was simulated in the CST Particle-in-Cell Solver. The simulations used the 3D magnetic field distribution of the permanent magnet assemblies. The electron beam distribution through the buncher is shown in Fig. 5. The energy modulation of the bunches, represented by the color differentials in and past the idler cavity, can be seen.

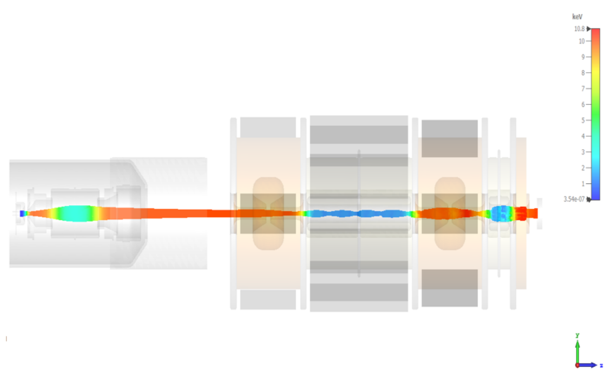

Figure 5: Electron beam distribution through the compact electron beam buncher.

A beam stop is placed immediately downstream of the buncher structure, and the collision current was measured and shown in Fig. 6. Within each 5.712-GHz period, the peak electron current reached up to 150 mA, compared to the average current of 34.9 mA. Based on the data presented in Fig. 6, the first harmonic current [5], which is the figure of merit evaluating the bunching level, was calculated to be 1.3 times the average beam current. This is a very high first harmonic current, considering that there is only one idler cavity.

CONCLUSIONS

A C-band (5.712 GHz) compact and efficient electron beam buncher was developed at Los Alamos National Laboratory for compact accelerator applications. The buncher uses space-charge enhanced bunching, and the RF cavities

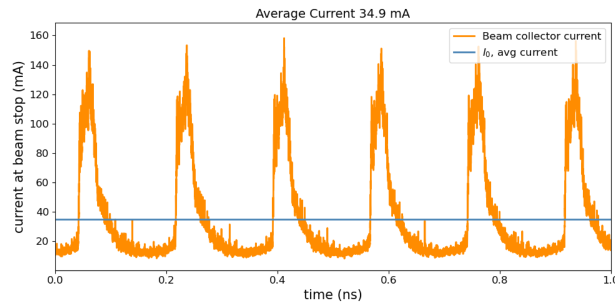

Figure 6: Collision current of the bunched electron beam on the beam stop setup at the exit of the compact electron beam buncher.

of the bunch are assigned like those in a klystron. The compactness of the buncher is enabled by the application of the electrostatic potential depression inserts.

The compact electron beam buncher circuit uses permanent magnet assemblies for providing continuously tunable focusing magnetic field. The mechanical design has been completed.

3D Particle-in-Cell simulations of the compact electron beam buncher was performed using high-fidelity magnetic field distribution provided by the permanent magnet focusing. The results predicted the output beam to possess sufficiently high first harmonic current, representing a significant bunching level.

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