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COMPRESSION OF RELATIVISTIC ELECTRON BUNCH TRAIN

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Abstract

We propose a method of compressing relativistic bunch train using a relatively compact solenoid installation. This magnetic compression setup allows for adjustment of the bunch interval and can compress electron beams at larger scales compared to setups of similar size. Our proposed method offers a more efficient approach to compressing relativistic bunch train.

INTRODUCTION

Over the past few decades, micro electron beam compression methods such as velocity bunching or traditional magnetic compression have received widespread attention and research [1–4]. These methods aim to compress the beam in time scales of picoseconds or even femtoseconds to meet the demand for very bright electron pulse in free electron lasers, colliders, and other applications.

However, the compression of electron bunch trains, also known as macro-pulse compression, has received little attention in the literature. Despite the many benefits of compressing macro-pulses, such as achieving efficiency close to 100% during power compression, manipulating a bunch train of relativistic electron beams typically requires large equipment. For example, the GELINA [5] facilityemploys a compression magnet with a diameter of 3 meters and a weight of 50 tons to compress the electron beam from 10 ns to 1 ns. In the Compact Linear Collider (CLIC) design, a delay line and two combiner rings with circumferences of 292 m and 438 m, respectively, are utilized to compress the drive beam from 5.8 us to 244 ns [6, 7].

To address this problem, we propose a relatively compact solenoid installation with a similar size to the GELINA magnet, but capable of manipulating electron bunch trains with a duration of tens of nanoseconds.

COMPRESSION PRINCIPLE

As illustrated in Fig.1, we utilize the spiral motion of electrons in a uniform magnetic field to fold the long trajectory into a compact volume. The spiral helix or period of the bunches is modulated for bunch interval compression.

The installation is shown in FIG.2. We employ a solenoid to generate an axially-oriented, static, uniform magnetic field inside it. The bunch train is injected into the cavity, spirals along the axis, and is extracted with a compressed interval.

Based on the installation, there are 2 different regimes for adjusting the interval between adjacent bunches.

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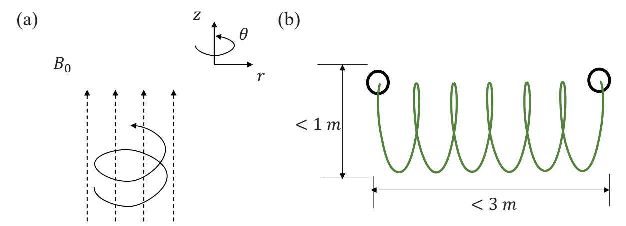

Figure 1: (a) Spiral motion of electron in uniform magnetic field. (b) Shceme of folding a long trajectory into a cylindrical volume

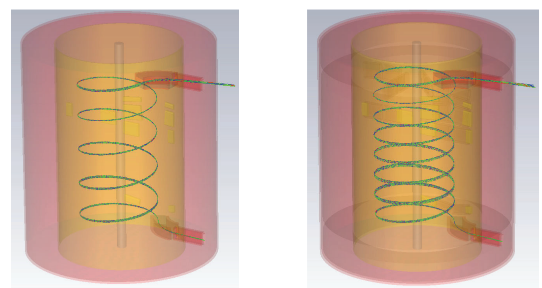

Figure 2: Spiral motion of electrons in the solenoid cavity

Spiral helix modulation

The principle of spiral helix modulation is illustrated in FIG.3. By placing several electromagnets inside the cylindrical cavity, time-varying local fields B_r can be generated on the bunches' spiral trajectory. This can deflect the injected bunches at different angles. After the deflection, the downstream bunches spiral with a larger helix and catch up with the upstream bunches in the spiral region.

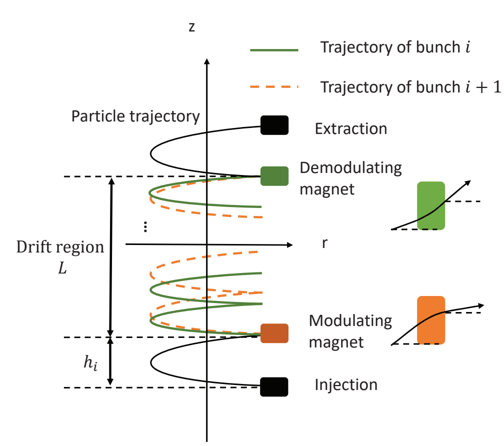

Figure 3: Principle of spiral helix modulation

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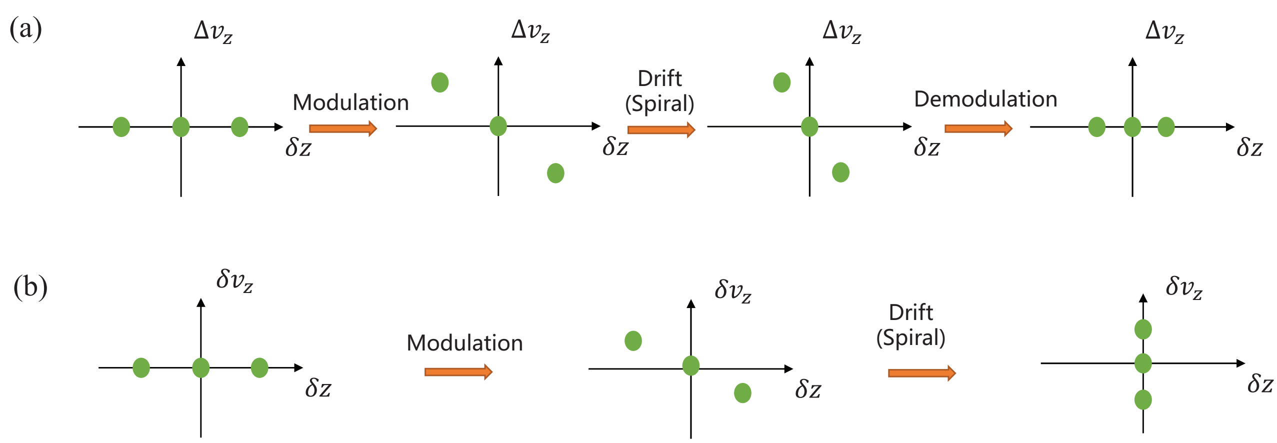

Figure 4: Phase-space transform of the bunch train in spiral helix modulation scheme. z is the axial direction. (a) Bunch train compress (b) Bunch train combination.

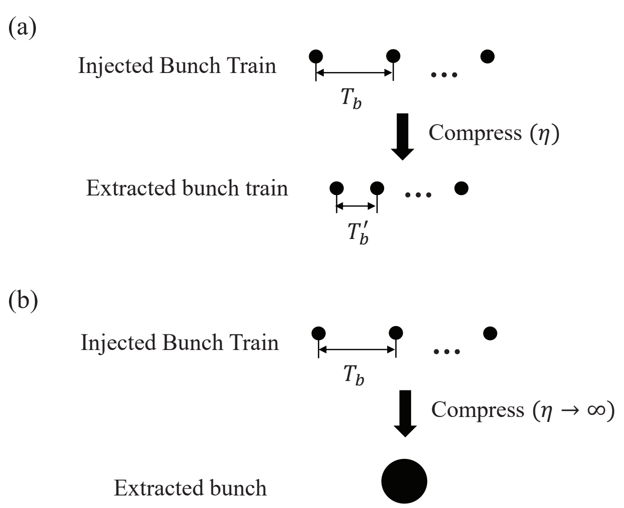

Figure 5: (a) Compression of electron bunch train. (b) Combination of bunch train.

After the spiral process, the bunch train is compressed by a factor:

$$\eta = \frac{T_b}{|T_b - NT_c|} \tag{1}$$

Where T_b is the time interval of injected bunches and T_c is turning period of bunches in the uniform magnetic field. In the spiral region, the rear bunch spirals N turn less than the front bunch in succession. Compression ($\eta > 1$) is achieved when N is greater than one, while electron bunch train dilution ($\eta < 1$) can be achieved when $|T_b - NT_c| > T_b$.

There is a limit case where, when $T_b = T_c$, all the bunches combine into one large bunch at the extraction port (as shown in FIG.5(b)). The design of the electromagnets placed in the cavity for compression and combination is different. The compression or combination procedure in the $z - z'$ phase space is illustrated in FIG.4.

Energy modulation

As the turning period of relativistic electron in a uniform field is proportional to it's energy. The bunch train compression can be also achieved by modulating the energy of the bunches before injection. FIG.6 shows the simulated trajectories of electrons with different energies in the solenoid cavity.

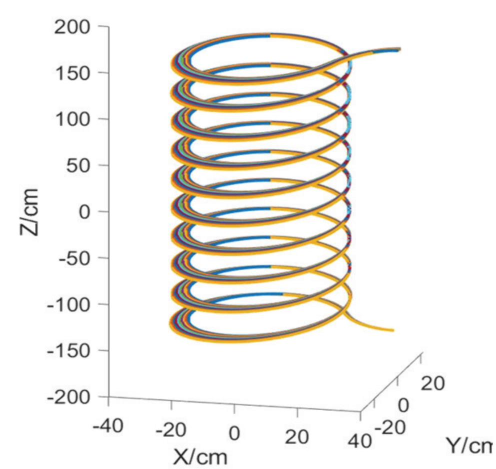

Figure 6: Simulated trajectories of electrons with different energy in the solenoid cavity.

In this compression scheme, the compression factor:

$$\eta = \frac{T_b}{|T_b - N\Delta T_c|} \tag{2}$$

$$\frac{\Delta T_c}{T_c} = \frac{\Delta E}{E_0} \tag{3}$$

Where ΔE is the energy difference of a bunch with respect to the reference energy E_0, and ΔT_c is the difference in the turning period of the bunch with respect to the reference bunch.

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The key feature of this scheme is that it can manipulate continuous electron beam if the energy chirp is continuous, allowing for finer manipulation of the beam.

The principle of this regime is similar to the GELINA compression magnet, but by utilizing the spiral motion, this installation can compress the beam over a larger time scale.

SIMULATION

Parameter specifications of the solenoid and electron beam in our simulation is listed in Table 1.

Table 1: Simulation Specifications

Parameter	**Value**	**Units**
Solenoid Diameters	0.8	m
Solenoid Length	5	m
Uniform Field	0.1	T
Beam Energy	6.5	MeV
Spiral Radius	25	cm
Turning Period	5.4	ns

The solenoid, injection/extraction magnets, and deflecting magnets were designed in CST Studio. Magnetic fields applied in the simulation were exported from the designs. Fringe field is the most challenging issue during the compression process.

In the Spiral helix modulation scheme, we were able to compress 10 bunches with a charge of 1 nC each by a factor of 10. The duration of the beam before and after the compression is 60 ns and 6 ns, respectively.

We also performed the special case of $T_b = T_c$, where a single bunch of 10 nC was formed at the extraction port.

In the Energy Modulation scheme, we compressed a bunch train with a repetition rate of 1.6 GHz, and obtained a bunch train of 100 GHz (W-Band) after extraction. The form factor of the extracted beam current was $F = 0.3$."

CONCLUSION

We have proposed a novel concept of relativistic bunch train compression, which has been verified through simulation. Compared to setups of similar size, such as chicane and GELINA compression magnets, this method can compress bunches on a distinctly larger scale and at higher intensities, opening up new possibilities for generating beams with ultra-large energy storage.

We plan to further optimize the magnetic design to achieve a larger dynamic aperture and improve the compression capability of the system. Additionally, we have devised some other compression methods based on this solenoid installation.

An experiment based on the energy modulation scheme is currently in preparation, and is expected to be conducted within the next year.

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