# An Injector-prebuncher for a Plasma Electron Accelerator

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## ABSTRACT

Optimum operation of a plasma beat-wave or wakefield accelerator requires an injected beam consisting of a train of electron bunches separated by the plasma wavelength, with each bunch in the train having a length much shorter than the plasma wavelength, and the capability of controlling the relative phase of the electron bunches and plasma wave. The typical plasma wavelength is about 0.1 mm, requiring a bunch length of about 10 to 20 μm, which is difficult to achieve with conventional RF based injectors. In this paper we describe an electron accelerator-buncher system based on a photoinjector and an FEL, which can satisfy the plasma accelerator requirements.

## INTRODUCTION

An injector of up to 25 MeV beam energy is proposed to supply the Plasma Beat Wave Accelerator (PBWA) [1] with a high quality ($\varepsilon$ = 0.5 $\pi$ mm-mrad at full energy) electron beam of sufficient intensity (~ 1 nC per pulse) to allow capture and acceleration by the PBWA of a significant number of electrons to the GeV energy range. The injector will be based on proven technology from the Saturnus laboratory [2], with upgrades of both the BNL RF gun [3], and the Plane Wave Transformer (PWT) accelerator [4]. The system will provide 1 nC average micropulse charge focused to a 100 μm spot diameter at the injection point. A FIR FEL is proposed as an optical pre-buncher. Phase locked pre-bunching of the electron pulse into 10 - 20 μm long bunchlets will allow control of the relative phase of the electron bunchlet and the plasma wave. Such control will aid in minimizing PBWA electron beam final energy spread and emittance. The optical pre-buncher/ final focus system may need to be an achromatic and isochronous system to second or perhaps third order to maintain the bunchlets shape after exiting the optical resonator.

## PBWA REQUIREMENTS

A PBWA operates by mixing two lines from a drive laser in a plasma whose parameters are chosen so that the beat between the laser lines matches the plasma frequency. We assume a multi-terawatt 1 μm laser system as the drive laser system for the PBWA. The PBWA requirements dictate the design of the injector so that efficient matching can occur. Table 1 shows the top level parameters upon which the design is based.

TABLE I

| Parameter | Design Value |
|---|---|
| Emittance (unnormalised, rms.) | 0.5 $\pi$ mm-mrad |
| Energy spread (rms.) | 2% |
| Injector beam energy | >2 MeV |
| Average charge in bunch (bunchlet) | 1 nC ($10^8$ $e^-$) |
| Bunchlet length | 30 - 60 fs |
| Bunchlet diameter (2$\sigma$) | <200 μm |
| Phase Control | |
| absolute | +\- 1 ps |
| relative | <30 fs |

Injection phase control of the bunchlets facilitates optimization of the PBWA for acceleration, reducing the energy spread and emittance of the PBWA accelerated beam. Absolute timing is relaxed because the electron pulse can be much longer than the laser pulse. However relative timing of the plasma beat waves with the electron bunchlets becomes necessary. A nonlinear optics control method of phase locking bunchlet formation to the beat wave produced by the lasers is necessary. Several possibilities exist to achieve this and detailed studies will be done to identify the most likely candidates so that the issue will be resolved before the optical bunching experiment is begun. We note that the options include: 1) Use of a beatwave-plasma interaction to produce 100 μm phase locked radiation to seed an FEL amplifier and; 2) use of nonlinear index of refraction changes in a plasma, due to a plasma beat-wave interaction, to control the optical path length, thus the relative phase, of 100 μm light.

The baseline injector system uses the technology of the Saturnus experiment. The Saturnus hardware represents all the hardware needed for the injector, except for the experiment specific final focus into the PBWA, and phase locking of the electron pulse to the PBWA laser system.

## INJECTOR DESCRIPTION

A standard RF power system consisting of a modulator and klystron runs a photo-cathode RF gun (0-5 MeV) and an PWT (pulse wave transformer) accelerator section (5-25 MeV). The electron beam generated in the gun is focused by bucking solenoids so that it has proper size entering the accelerator. X-Y steering magnets correct for any small mechanical misalignments. After exiting the accelerator section the beam travels through a beamline guided and focused by dipole and quadrupole magnets. These magnets match the electron pulse into the FIRFEL for prebunching. A final transport section matches the beam into the PBWA for acceleration by the plasma wave.

The modulator and klystron provide up to 35 MW, approximately 7 MW to the electron gun and the rest available to the PWT. The design of the modulator is taken from the present modulator for the Saturnus experiment, capable of running at 5 pps. The klystron will be a SLAC XK-5 of which UCLA currently has two available for this project.

Fourth harmonic light of the PBWA laser drives the photocathode. The gun itself is the second generation of the successful Brookhaven National Laboratory rf gun. A slight modification of the length of the first cavity, to 0.6 $\lambda$, results in an increased electron beam brightness (a decrease in beam emittance) over the original "half cavity" design.

The PWT is a high gradient standing wave accelerator. Several engineering and fabrication improvements are proposed for the new injector: A simplification of the internal cooling of the structure; use of all metal sealing surfaces for greater radiation resistance and better vacuum properties; redesign of the "disks" to reduce the maximum surface gradient. This improved PWT has been fabricated and tested with low level RF power and has been installed into the Saturnus beamline. In order to reach 25 MeV two PWT structures will be used.

## THE FEL AS AN OPTICAL BUNCHER

The requirements on the pre-buncher are that ~10 $\mu$m bunches spaced 100 $\mu$m apart are injected into the plasma beat wave accelerator with emittance and energy spread within the acceptance of the PBWA. An FEL naturally bunches electrons onto a fraction of the optical wave being amplified, one wavelength apart. From this is it is quite clear why an FEL can be used as the PBWA pre-buncher.

Matching operation of the pre-buncher to produce the beam desired for injection into the PBWA leads to setting the operating point of the FEL in terms of energy, undulator length, and field strength.

GINGER calculations for a master oscillator-power amplifier (MOPA) FIR FEL configuration have been done to begin examining the performance of a pre-buncher. Table II gives the GINGER parameters of the electron and optical beams studied for the oscillator and the amplifier.

Table II

| **Electron Beam Parameters Oscillator and Amplifier** | |
|---|---|
| Electron beam energy | 21 MeV |
| Micropulse current | 150 A |
| Micropulse length (fwhm) | 12 ps |
| Micropulse spacing | 10 ns |
| Normalized emittance (edge) | 10 $\pi$ mm-mrad |
| **Resonator Parameters, osc.** | |
| Single pass gain | 2.4 |
| Power in spontaneous emission after 1 pass | 15 W |
| Saturated power (peak) | 180 MW |
| Resonator length | 1.5 m |
| Round trip time | 10 ns |
| **Undulator Parameters Oscillator and Amplifier** | |
| Undulator period | 4 cm |
| Undulator length, osc. | 1 m |
| Undulator length, amp. | 0.8 m |
| On axis magnetic field | 1.04 T |
| path length correction factor $K^2/2$ | 11.3 |

The GINGER code test case is based on a parabolic electron bunch in z of total length 16 ps. The undulator is linear with external quadrupoles providing focusing in the wiggle plane.

The oscillator is assumed to have 60% net cavity reflectance, with a net cavity detuning that is 0% of slippage.

Figure 1 displays results from GINGER showing the bunching of the electrons at the end of the amplifier undulator. The first pulse displayed, at a time 1.33 ps into the bunch, demonstrates the excellent bunching possible through the FEL mechanism. The majority of electrons are clearly bunched very sharply in phase over

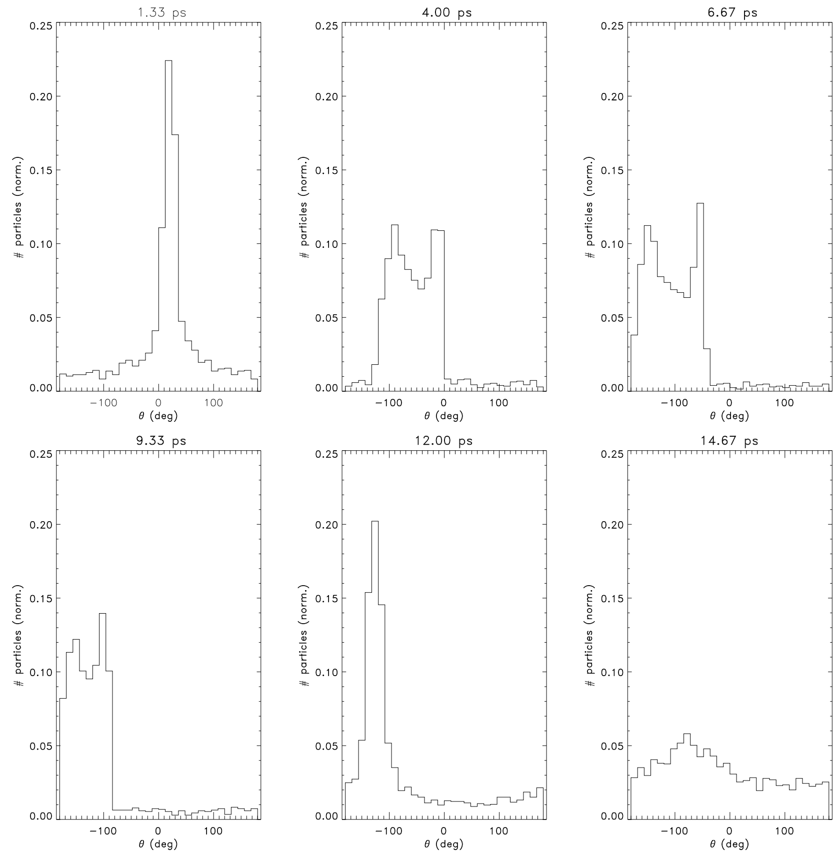


Figure 1:
Electron Beam bunching at six slices in time at the amplifier undulator exit.

~60°, corresponding to less than 20 μm. The forward part of the electron pulse is well bunched because the optical fields propagate from the rear to the front due to the slippage of the electron beam. The bunching parameter is about 0.7. To increase the number of well bunched slices, we will consider in future calculations two potentially beneficial effects: 1) tapering the undulator, and; 2) use of a waveguide in the amplifier to reduce slippage.

The amplifier needs a source of 100 μm light to start it. Two possibilities exist: The FEL oscillator could be built as the source. The MOPA configuration clearly provides a complete solution to the problem of getting 100 μm light, but is expensive and does not solve the phasing problem between the bunchlets and the PBWA beatwave. A second possibility would be to use the beatwave to produce a 100 μm seed for the FEL amplifier directly. This gives automatic phasing between the bunchlets and the wave. An initial calculation indicates that injecting the two lines from the drive laser into a plasma will produce at least 100 kW of coherent 100 μm light in a f/1 cone angle. As can be seen from Table II this power is several orders of magnitude greater than the spontaneous emission at the end of the first pass.

# REFERENCES

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