MULTIBUNCH BEAM PHYSICS AT FACET*

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Abstract

Plasma wakefield studies are normally conducted as single-shot experiments. Here, single-shot means that the plasma returns to its original state before the next bunch passes through the plasma. The time scale for the plasma to return to equilibrium is 10-100 ns, which is comparable to the bunch separation in proposed linear colliders. The SLAC linac typically delivers beam at a rate of 10 Hz to FACET, but can also be operated in a manner that delivers two electron bunches per RF pulse to FACET. We explore operating modes with beam separations as small 5.6 ns so that high repetition rate plasma wakefield acceleration can be studied at FACET.

INTRODUCTION

The SLAC linac provides electron bunches with total beam charge of 3.2 nC to FACET experiments. The beam originates at Sector 0 from a thermionic cathode gun, passes through the sub-harmonic buncher for longitudinal compression, is captured and accelerated in the Sector 1 s-band linac and sent to the North Damping Ring (NDR) for beam cooling. After the emittance is damped in the ring, the beam is extracted into the Sector 2 linac, accelerated to 20.35 GeV, and delivered to Sector 20 for final compression and focusing. An overview of the linac and associated systems is given in Fig. 1. Each system imposes its own constraints on the possible bunch parameters and inter bunch spacings.

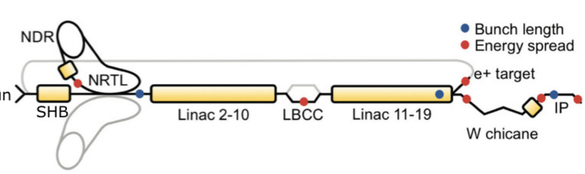

Figure 1: Overview of Linac with affected subsystems and diagnostics for multi-bunch operation.

BEAM GENERATION AND CAPTURE

Source

The electron source is a thermionic cathode driven by a multi-channel pulser. The pulser is a circuit with two planar triode amplifiers that couple into a common amplifier driving the cathode. The two triodes can be fired independently to produce electron pulses from the cathode with arbitrary separation in time. The gun can generate up to 27 nC of charge in a single pulse. We look to generate two pulses with 3.2 nC each. This can be achieved without changing the existing gun hardware [1].

Subharmonic Buncher

Immediately after the beam is generated it is captured in the sub-harmonic buncher (SHB). The SHB is operated at the $1/16^{th}$ sub-harmonic of the s-band linac. The bucket spacing for the SHB is 5.6 ns. The SHB bucket size sets the interbunch spacing in the rest of the machine. Without the SHB, most of the beam does not get captured in the linac and there is the potential for radiation damage in the injector. All of the interbunch spacings considered in this paper are multiples of 5.6 ns.

The longitudinally compressed bunches are captured in an s-band bucket at the start of Sector 1 and accelerated to 1.19 GeV before being sent to the NDR via the North Linac-to-Ring arc.

NORTH DAMPING RING

Kickers

A loaded ferrite kicker magnet with a flat-top of 30 ns kicks the bunches into the ring. This magnet was designed to have an extremely sharp rise and fall time, so as not to disturbed another bunch in the ring, which was typical during SLC operation. A second kicker magnet is located on the opposite side of the ring and is used to extract the bunches. This magnet is identical to the injection kicker except that it has a different pulse forming network that uses a Blumlein generator to produce an extremely flat pulse to the magnet [2]. The field in the magnet provides a uniform 7 mrad kick for more than 60 ns. The injection and extraction kickers set limits on the maximum separation between the two bunches. The maximum bunch spacing that is consistent with the NDR RF and SHB RF is 61.6 ns. The injection kicker would have to be equipped with a similar PFN as the extraction kicker to achieve this separation.

Instabilities

The NDR limits the bunch charge and separation in another manner due to single-bunch and coupled beam instabilities. The single bunch instability is a short range, microwave instability. With 3.2 nC per bunch, the ring is operated above the threshold for the instability. However, at this charge the instability is weak and does not degrade the bunch quality [3]. Note that having two 3.2 nC bunches

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in the ring instead of one has no effect on this instability because it is very short range.

On the other hand, a pi-mode instability arrises in the ring due to bunch coupling to HOMs in the RF cavities. The bunches exhibit both zero mode and pi-mode oscillations with respect to the ring RF. The zero mode oscillation is damped by synchrotron radiation but the pi-mode is not. To counteract this instability, a passive cavity was added to the ring in 1992 [4]. At the time, the cavity was tuned to 1062.4 MHz, just below the 125^{th} revolution harmonic to accommodate two bunches with a bunch separation $t_i = 61.6$ ns. The cavity has a movable plunger that can be adjusted to match the frequency of the pi-mode oscillation for each of the different bunch separations tested at FACET.

MAIN LINAC

The beam is extracted from the NDR and passes to the main linac via the North Ring-to-Linac arc. The bunches pass through a compressor cavity at the zero crossing of the RF and this imprints a linear chirp on the beam. The beam is compressed down to 500 μm bunch length by the R_{56} of the chicane and then captured in an s-band bucket in the linac. Once the bunches reach the linac, the trailing bunch is affected by longitudinal and transverse wakefields of the leading bunch. Those two effects are discussed below.

Beam Loading

The leading bunch absorbs energy as it passes through the accelerating cavities. This energy cannot be replaced with additional energy from the klystron if the inter bunch spacing is very short. This effect, called beam loading, results in the trailing bunch receiving less energy after passing through the cavity as compared to the leading bunch. The voltage drop induced in the cavity by the leading bunch is given by $V_w = 2eNL\kappa_z$ where eN is the bunch charge, L is the cavity length, and $\kappa_z = 20$ V/pc/m is the fundamental wakeloss factor for the SLAC s-band cavities. The trailing bunch sees the accelerating voltage reduced by this amount.

If the cavity phase is not zero (on crest), the trailing bunch also sees a different RF phase as compared to the leading bunch. The phase the trailing bunch sees is given by Eq. 1 and explained visually in Fig. 2.

$$\phi' = \tan^{-1}\left[\frac{V_{RF}\sin\phi}{V_{RF}\cos\phi - V_w}\right] \tag{1}$$

The phase shift effect is significant at FACET because each sector in the front half of the linac is phased differently. The chirping scheme depicted in Fig. 3 was designed to minimize the effect of wakefields on the beam at low energy while still achieving the necessary chirp for compression in the Sector 10 chicane. The phase in each sector is an integer multiple of the Decker Phase, which is usually about 10^o. This rather complicated chirping scheme means that the trailing bunch will we see a different phase relative

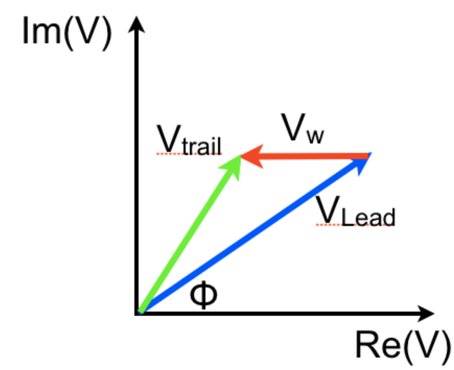

Figure 2: Phase diagram showing the RF voltage and phase difference seen by the trailing bunch.

to the leading bunch in Sectors 2 though 10. The resulting phase shifts are listed in Table 1.

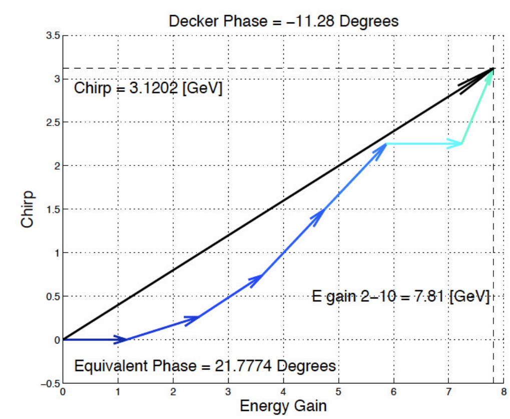

Figure 3: FACET front-end chirping scheme. Each phase arrow represents one sector and is an integer multiple of the Decker Phase.

Table 1: Sector by Sector Phase Shifts for a Decker Phase of 10^o. Note that Sectors LI07 and LI08 are omitted from the table since they are not powered.

Sect.	L [m]	$V_{RF} [GV]$	ϕ	V_w [MV]	$\Delta\phi$
LI02	75.5	1.59	0^o	9.66	0^o
LI03	96.0	1.85	10^o	12.3	0.066^o
LI04	84.0	1.72	20^o	10.8	0.12^o
LI05	97.4	1.88	30^o	12.5	0.19^o
LI06	97.4	1.88	30^o	12.5	0.19^o
LI09	97.4	1.88	0^o	12.5	0^o
LI10	67.0	1.44	50^o	8.57	0.26^o

Beam loading reduces the energy of the second bunch by 0.8% in Sectors 02-10 and 0.5% in Sectors 11-20, relative to the first bunch. This does not pose a problem because the full-width half-maximum energy apertures of the Sector 10 and Sector 20 chicanes are 5% and 4% respectively. The effective phase of the trailing bunch with respect to the

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leading bunch is 23.49^o compared to 23.38^o at the Sector 10 chicane. Although this effect seems small, it is amplified by the difference in compression that each bunch will see in the Sector 10 chicane, which leads to different wakefields in Sectors 11-20. Short-range longitudinal wakefields effectively chirp the extremely short beams, and therefore they will be compressed differently in the Sector 20 chicane. This extremely non-linear problem will be studied in simulation to determine the severity of the effect.

RF Pulse Compensation

For bunch separations larger 5.6 ns, RF pulse compensation can be used to correct for the beam loading effect. The SLEDed RF pulse fills the cavity over a period of several microseconds according to the parabolic form depicted in Fig. 4. Typically, the bunch is accelerated at the crest of the pulse. In order to accommodate multiple bunches per pulse, the bunches are instead accelerated on the rising slope of the pulse, with the leading bunch slightly lower on the slope and the trailing bunch slightly higher. For a bunch separation of 16.8 ns (three times the minimal separation), the effect of beam loading can be totally compensated [5].

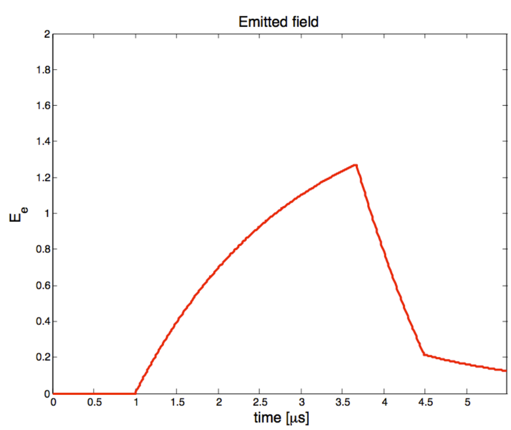

Figure 4: Temporal shape of the SLEDed pulse in the s-band cavity.

Transverse Wakefields

If the leading bunch is misaligned with respect to the RF cavities, the trailing bunch may see a significant transverse kick from the wakefields in the cavity. Fig. 5 shows that there is a minimum in the transverse wake strength at around 5 ns. For this reason, it is advantageous to choose the 5.6 ns bunch spacing for our first tests of multibunch operation. The size of the second envelope in Fig. 5 is indicative of the wake strength out to 60 ns, which is the largest bunch separation possible at FACET [6].

CONCLUSION AND OUTLOOK

The scientific merit for multibunch studies at FACET is very high considering the recent advances in plasma wakefield technology. It is critical to demonstrate that PWFA is

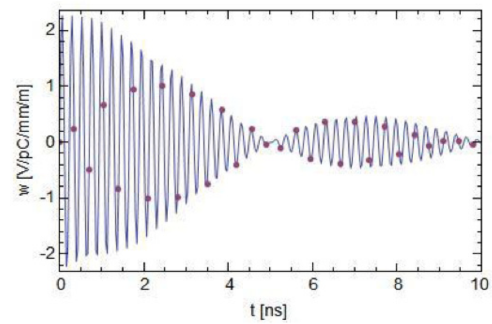

Figure 5: The time domain transverse wakefield in the SLAC s-band cavity.

stable and reproducible at high repetition rates before this technology can be used in light source or collider applications.

Relatively few systems need to be modified in order to achieve in the multiple bunches at FACET. However, from an operations perspective, the multibunch mode is challenging because many diagnostics, including BPMs, cannot resolve the closely spaced bunches, and the timing windows are very tight for injection and extraction at the NDR. Some of these issues might be mute if the thermionic cathode is replaced by an LCLS-style photocathode. This has been proposed for FACET or FACET II. On the other hand, the phase shifts in the main linac are still an important issue, and would have to be dealt with for any high-charge, multibunch mode at FACET, regardless of the beam source.

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