VELOCITY BUNCHING EXPERIMENT AT THE NEPTUNE LABORATORY

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Abstract

In this paper we describe the rectilinear compression experiment at the Neptune photoinjector at UCLA. The electron bunches have been shortened to sub-ps pulse length by chirping the beam energy spectrum in a short S-band high gradient standing wave RF cavity and then letting the electrons undergo velocity compression in the following rectilinear drift. Using a standard Martin Puplett interferometer to characterize coherent transition radiation from the beam, we measured bunch lengths as short as 0.4 ps with compression ratio in excess of 10 for an electron beam of 7 MeV energy and charge up to 300 pC.

INTRODUCTION

In recent years electron beam users have increased their demands for high brightness beams in short sub-ps pulses. These beams find applications in the advanced accelerator community for injection into short wavelength high gradient accelerators [1], or as plasma wake-field drivers, and in the light source community for short wavelength SASE Free Electron Laser[2] and for Thompson-scattering generation of short X-ray pulses [3]. Recent designs of systems capable of delivering high brightness very short electron beams include the use of conventional photoinjectors in conjunction with magnetic compressors. While the magnetic compression scheme has been proved successful in increasing the beam current, the impact on the phase space has been shown to be quite dramatic [4]. An alternative scheme that could preserve the phase space quality while still shortening the beam to sub-ps bunch length has been recently proposed as an injector for X-ray Free Electron Laser, by Serafini and Ferrario [5]. This scheme, commonly known as "velocity bunching" is an elaboration of the old idea of RF rectilinear compression to the RF photoinjector system [6]. The idea is based on the weak synchrotron motion that the beam undergoes at moderate energies in the RF wave of a linac accelerating structure. The compression happens in a rectilinear section so that the damage suffered by going through bending trajectories is avoided. A main ingredient of the Serafini and Ferrario recipe to produce high brightness sub-ps electron beam is to integrate this compression section in the emittance compensation scheme, by keeping the transverse beam size under control through solenoidal magnetic field in the region where the bunch is compressing and the electron density is increasing.

A small variation inside this framework is the thin lens

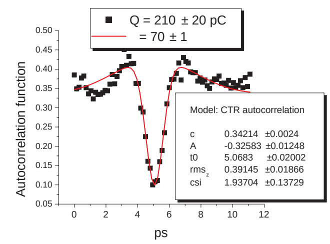

Figure 1: Results of Neptune ballistic compression experiment

version of velocity bunching. Here the synchrotron motion of the electrons inside the RF structure is very limited. There is almost no phase advance inside the longitudinal lens and all the bunching happens in the drift following the linac. In this paper we describe an experimental study of the above configuration.

EXPERIMENTAL SETUP

At the Neptune laboratory at UCLA [4] a 4 ps rms long laser pulse hits a single crystal copper cathode inside a 1.6 cell RF gun. The photoelectrons generated are then accelerated by the RF fields and go through the emittance compensation solenoid. At this point the beam can be energy chirped inside a 6+2 $\frac{1}{2}$ cell S-band PWT RF cavity. There is the capability of controlling and measuring independently the phases of the two accelerating structures allowing us to test the ballistic bunching scheme. Downstream of the linac an aluminum foil can be inserted and the transition radiation generated is collected by a parabolic mirror and reflected to a Martin Puplett autocorrelator for pulse length diagnostic [7]. There are also four chicane dipoles along the beamline and two of them can be turned on in a 45 degrees dipole mode. On the 45 degrees beam line there is a quadrupole lens and a Yag screen for emittance measurement via quad scan.

LONGITUDINAL DYNAMICS

Ballistic bunching can be viewed just as a thin lens version of the more general velocity compression mechanism. In this configuration, the phase advance of the electrons going through the longitudinal lens (the PWT linac) is few RF degrees and all the compression happens in the following drift. The important difference with the long RF-structure slow-wave version of velocity bunching is that the beam is

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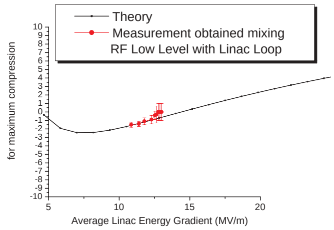

Figure 2: Phase of maximum bunching vs. Linac Accelerating gradient

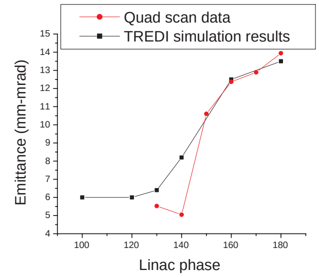

Figure 3: Emittance growth vs. PWT linac phase. Experimental results and simulations

extracted very close to the zero phase of the RF bucket and the RF non-linearities that in that case dominate the final bunch length are greatly reduced. One simple way to understand the ballistic bunching is to consider the time of arrival difference for particles having different velocities. When the time of arrival difference compensates the difference in the longitudinal position, the bunch length will be minimum and that is the maximum compression point. A relation between the parameters of ballistic compression valid to first order neglecting space charge and phase advance inside the PWT Linac can be written:

$$\frac{\Delta p}{p^3}L = \frac{E_{linac}\cdot\cos(\phi)\cdot k\cdot\Delta z}{(E_{gun}+E_{linac}\cdot\sin(\phi))^3}L = \Delta z \qquad (1)$$

where L is the distance from the RF structure, E_{linac} and E_{gun} are the energy gain of the PWT linac and the gun respectively, k is the RF wavenumber and ϕ is the Linac phase. We measured the pulse length in the frequency domain by Coherent Transition Radiation interferometry. For 210 pC of charge and 70 degrees off crest in the PWT cavity, we obtain the interferogram shown in fig.1. The data analysis yields a pulse length of 0.39 ps. The peak current of the bunched beam is in excess of 500 Amps. It is worth noticing the compressed beam is shorter than what was possible to get with magnetic compression for comparable beam charge, confirming the fact that in this case a more linear part of the RF wave is sampled. The predictions from the first order approximation given in (1) have been experimentally verified by measuring the compression phase changing the energy gradient in the Linac (fig. 2). The RF-cavity phase can be measured with a very small error by mixing the RF fields inside the structure with a reference RF-clock, at the same time the phase for maximum compression is easily determined by maximizing the Coherence Transition Radiation signal on the bolometer detectors. The agreement with the analytical formula is very good. Note that there is an important cancellation effect. As we decrease the energy gradient in the Linac, the beam is getting less energetic and less rigid to a rotation in the longitudinal phase space so that the adjustment of the phase to maintain the compression condition is minimal.

TRANSVERSE EMITTANCE MEASUREMENT

For optimal compression the beam runs through the high gradient structure far from the crest of the RF wave so that the energy spread at the exit of the Linac is very large. For example, for the case in which the focus of the longitudinal lens is 3 m downstream on the beamline, the RF phase was set 70 degrees off crest, resulting in a energy spectrum extending from 5 MeV to 9 MeV. This is a limitation to the determination of the transverse projected emittance because the energy spread translate to an angle spread and will appear to all measurement techniques (that are trace space measurements) as unphysical transverse emittance. On the other hand, the energy is correlated with the longitudinal position of the beam and with a small window of acceptance in energy, a longitudinal slice of the beam can be selected. Experimentally, we used the 45 degrees dispersing bending dipole configuration to select the central beam slice over which a vertical quad scan emittance measurement was performed. We measured the vertical phase space parameters of the electron beam varying the phase of the linac to understand the effect of the compression on the transverse dynamics of the beam.

ANOMALOUS VOLUME COMPRESSION

The experimental data show an increase in emittance even for phases for which the beam is not yet fully compressed. To completely understand this, it requires a deeper look into the dynamics of a chirped beam going through the bending magnet that we used as a slice selector in the measurement. For the vertical phase space, the bending magnet is in fact just a drift, but if we look at physical beam volume in x-s configuration space, we observe a strong compression if the beam is chirped in energy with particles with higher energy being in the tail of the beam. Note that a bending magnet has a negative R56 so that the compression is anomalous. The sizes of the projections of the beam density onto the curvilinear longitudinal axis s or onto the transverse dimension x and y increase as the beam bends, but the three-dimensional physical volume of the beam gets smaller. It is an effect that is ultimately due to the correla-

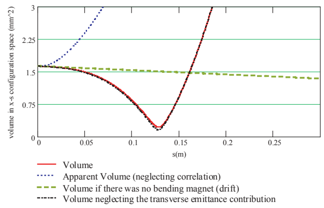

Figure 4: Anomalous compression for a beam chirped by phasing the PWT Linac 70 degrees off crest. The initial beam sizes at the entrance of the dipole magnetic field are $\sigma_x = 2.8mm, \sigma_s = 0.6mm$. The minimum volume point is 12 cm inside the magnet and the compression factor is 4.7.

tions in the configuration space introduced by the bending magnet. The effect of this electronic density spike at the cross-over point is dramatic for the electron beam quality especially at moderately relativistic energies where space charge forces are dominating the dynamics of the beam. A similar effect was observed in the Neptune magnetic compression experiment, where configuration space mixing was the origin of the observed emittance growth [4].

We analyze the problem of a chirped beam going through a bending magnet with a simple linear matrix calculation to illustrate the anomalous compression dynamics. The details of the calculation are given elsewhere. [9]. The result is that neglecting space charge forces and the contribution of the transverse emittance, we can write for the final configuration space volume the following:

$$V_f = \sqrt{\sigma_{xx}(\sigma_{ss}+2\sigma_{s\delta}R'_{56}+\sigma_{\delta\delta}R'^2_{56})+R^2_{16}\left(\sigma_{ss}\sigma_{\delta\delta}-\sigma^2_{s\delta}\right)} \tag{2}$$

where s is the longitudinal coordinate along the beam path, R is the bending radius and γ is the design energy. R'_{56} can be written as:

$$R'_{56} = \frac{s}{\gamma^2} + R\cdot\sin\left(\frac{s}{R}\right) - s\cdot\cos\left(\frac{s}{R}\right) \tag{3}$$

a positive quantity increasing with distance (in the ultrarelativistic case, $\simeq s^3$), and R_{16} is the usual dispersion function, also an increasing function of the distance s. The volume at the beginning of the bend is $\sqrt{\sigma_{xx}\cdot\sigma_{ss}}$.

If the beam initially has a negative energy-position correlation ($\sigma_{s\delta} < 0$), somewhere along the beam-path the term multiplying σ_{xx} in (2) is zeroed and the volume goes through a minimum (fig. 4). This minimum volume point, the anomalous compression point, corresponds to the position along the beam line where the more energetic particles in the tail of the beam overtake *in the cartesian coordinate* z the less energetic ones. Not only the space charge effects become more significant because of an absolute increase in the total electron density, but more importantly this increase is localized to a region in the physical space in which a crossover happens. This implies a strong electric field gradient inside the bunch that is ultimately the cause for the quality degradation.

Full three-dimensional simulations with the particle tracking Lienard-Wiechert potential based code TREDI [8] confirm the validity of the linear analysis and, in fact, the results for the emittance growth match quite well the experimental data (fig. 3).

CONCLUSION

The Neptune ballistic bunching experiment demonstrated the efficiency of the rectilinear RF compression. A compression ratio in excess of 10 was achieved due to the strong suppression of the effect of the RF-non linearities. Experimental investigation of the transverse phase space quality showed emittance degradation. A deeper look into the beam dynamics shows that the technique used to select a small energy spread slice affects the beam quality in a serious way. A first order linear analysis is performed to quantify the anomalous beam compression of a chirped beam going through bending magnet. Three-dimensional simulations are in reasonable agreement with the experimental data.

The Neptune experiment points out the deleterious effect of crossovers in a space charge dominated beam dynamics, but because of the lack of post-acceleration we can not make conclusive statements on the quality of a beam compressed with a velocity bunching scheme. Future experiments are needed to investigate the full potential of the velocity bunching method for increasing the brightness of photoinjector beams, and the use of the magnetic solenoids to keep the beam phase spaces under control. One important point to be addressed is to investigate the difference between the thin lens version 'ballistic' bunching and the long version of the rectilinear compressor.

ACKNOWLEDGEMENTS

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REFERENCES

[1] C. E. Clayton,L. Serafini, IEEE Trans. On Plasma Science, 24, 400 (1996)

[2] Linac Coherent Light Source (LCLS) Design Report, Tech. Pub., SLAC-R-521 (1998).

[3] S. Anderson *et al.* these proceedings

[4] S. Anderson *et al.* Proc. of PAC 2001, p. 89 (2001)

[5] L. Serafini, M. Ferrario, AIP Conference Proceedings 581, 19th pp. 87 (2001)

[6] X. J. Wang *et al.*, Phys. Rev. E, 54, 3121 (1996)

[7] A. Murokh *et al.*, in AIP Conf. Proc. 472, 38 (1999)

[8] L. Giannessi et al., Nucl. Instr. Meth., 393, 434, 1997

[9] P. Musumeci *et al.*, Proceedings of 2nd ICFA High Brightness Beams Workshop, Chia Laguna, CA (2003)