A VELOCITY BUNCHING SCHEME FOR CREATING SUB-PICOSECOND ELECTRON BUNCHES FROM AN RF PHOTOCATHODE GUN

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Abstract

Sub-picosecond electron bunches are in demand for various applications including Free Electron Lasers and electron diffraction experiments. Typically, for Free Electron Lasers, a multiple picosecond scale bunch is produced from a photoinjector with compression achieved via one or more magnetic chicanes by providing an appropriate energy chirp to the bunch in the preceding linac sections. This approach is complex, requiring many components, often including a higher harmonic linac section to linearise the longitudinal phase-space, and careful tuning in order to minimise emittance blow-up due to coherent synchrotron radiation. We present a scheme to deliver sub-picosecond electron bunches, based on a normal conducting RF gun and two short linac sections, one for providing velocity bunching and the second to capture the compressed bunch and accelerate to tens of MeV where the beam properties are then essentially frozen.

INTRODUCTION

Normal conducting S-band RF guns are often the gun of choice for modern FELs. They usually provide very low emittance beams, however, FELs typically require fs scale bunches which are usually obtained by multiple stages of magnetic compression. Using velocity bunching at low energy would be an alternative to magnetic compression and avoids the emittance degradation that occurs in dipoles due to coherent synchrotron radiation. We present ASTRA simulations which show the effectiveness of such a velocity bunching scheme.

ELECTRON GUN

As an example, fieldmaps from the ALPHA-X gun [1] have been used in these simulations. This is a 2.5 cell S-band RF gun with a copper photocathode. A solenoid surrounds the cavity and a bucking coil zeroes the magnetic field at the cathode. The peak on-axis electric field was set to 100 MV/m. Thermal emittance is included in the simulations as per LCLS measurements of 0.9 mm mrad per mm rms of a flat-top laser spot [2].

VELOCITY BUNCHING

Velocity bunching occurs by imparting a time-velocity chirp along the bunch by passing it through an RF cavity at the correct zero-cross phase. The electrons at the tail of the bunch are then faster than the electrons at the head, and thus, over time, the bunch naturally compresses.

After the gun, the bunch expands longitudinally due to space charge forces. Applying an off-crest gun launch phase can help to mitigate this effect. A dedicated buncher cavity has been placed as close as reasonably possible to the gun in order to minimise the extent of this space-charge de-bunching.

The buncher cavity used is a 2 m long normal-conducting S-band RF acceleration section. A shorter cavity does not provide the required velocity modulation, as shown in Figure 1, and longer cavities are unnecessary and further constrain the transverse beam dynamics. Since the cavity is relatively long and the beam not fully relativistic, phase slippage results in the beam gaining ~ 5 MeV in energy.

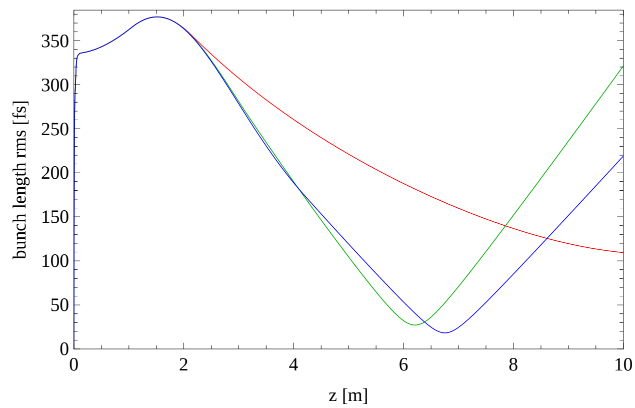

Figure 1: Velocity bunching with a 7.5 MV/m buncher cavity of length 1 m (red), 2 m (green) and 3 m (blue). The cavity entrance position is fixed at 1 m.

Capture Cavity

As Figure 2 shows, the buncher cavity can be used to compress a 10 pC bunch to less than 30 fs rms. The waist occurs close to the 6 m point, after which the bunch expands again. In order to capture and further accelerate the short bunch, a 2 m long linac section has been placed at the waist.

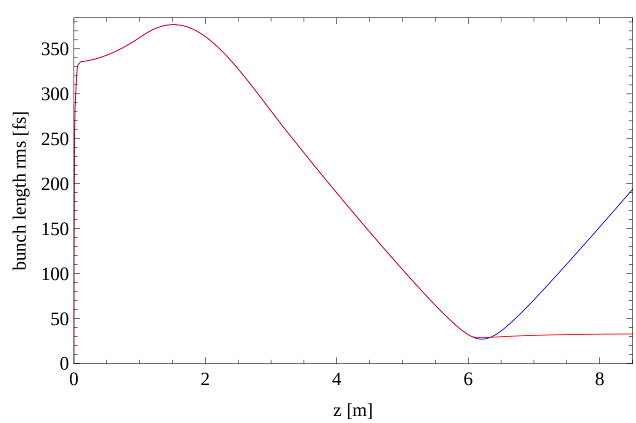

Figure 2: Evolution of bunch length with (red) and without (blue) the capture cavity for a 10 pC bunch.

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TRANSVERSE FOCUSSING

Without any post-gun transverse focussing, the beam size increases in the buncher which subsequently degrades the emittance. Two options have been investigated to control the transverse beam size, one is wrapping solenoids all the way around the buncher cavity, and the second is to install a small solenoid at the exit of the buncher. Figure 3 shows examples of transverse and longitudinal beam sizes, and emittance for a 10 pC bunch.

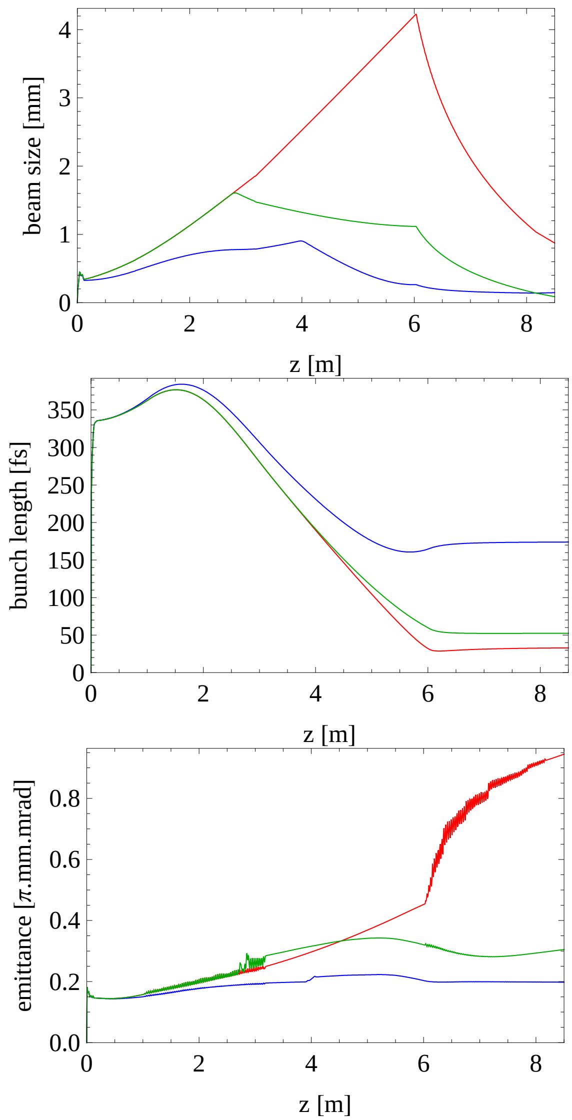

Figure 3: Rms beam size, bunch length, and emittance for the schemes with no solenoids (red), solenoids surrounding the buncher (blue) and just one small solenoid at the exit of the linac (green) for a 10 pC bunch.

OPTIMISATION

A genetic/evolutionary optimisation algorithm was used to determine the beamline settings. This utilises a non-dominating sorting technique similar to NSGA-II [3]. The algorithm allows one to optimise for multiple objectives so that, in this case, the trade-off can be seen between transverse emittance and bunch length. 100 generations of 60 simulations each were performed for bunch charges of 10, 100 and 250 pC, for both the case with long solenoids around the buncher cavity and the case a small solenoid at the end of the cavity. The optimiser was set to adjust the initial laser spot size and pulse duration, gun gradient and phase, buncher gradient and both solenoid fields. The buncher phase was fixed.

It was found that for 10 pC, the short solenoid at the end of the buncher provided better performance, but at the higher charges better performance was found with solenoids wrapped all the way around the cavity. Figure 4 shows the optimisation fronts for the three charges considered. It can be seen that less than 50 fs rms bunch lengths can be achieved at all charges however, at 100 pC, emittance can be kept around 1 mm mrad.

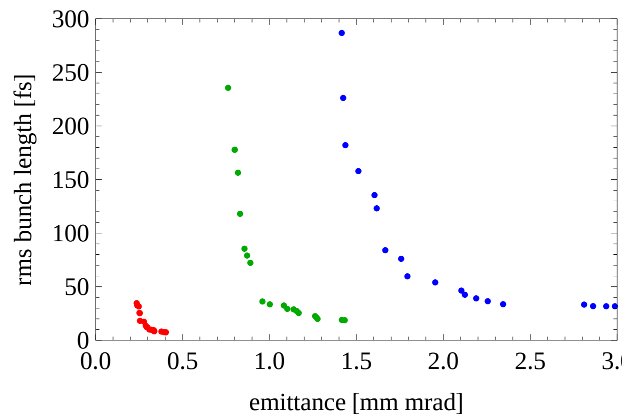

Figure 4: Optimisation fronts for 10 pC (red), 100 pC (green) and 250 pC (blue).

Figure 5 shows the current profile and slice emittance for one of the 100 pC solutions for a 100,000 macroparticle simulation. This has bunch length less than 25 fs rms, yet emittance (both projected and slice) is just over 1 mm mrad. It also has a peak current above 3 kA. Table 1 details the beamline parameters used and Table 2 summarises the beam parameters for this solution.

Table 1: Optimised Beamline Parameters for 100 pC

Parameter		Units
Laser spot diameter	1.80	mm
Laser pulse length (rms)	50	fs
Gun peak field	71.5	MV/m
Gun phase	-10	°
Gun solenoid peak field	0.246	T
Buncher peak field	14.6	MV/m
Buncher solenoid peak field	0.039	T

Table 2: Optimised Beam Properties

Parameter		Units
Bunch charge	100	pC
Emittance (projected)	1.10	mm mrad
Bunch length (rms)	23	fs
Peak current	3340	A
Energy spread (rms)	187	keV
Energy	50	MeV

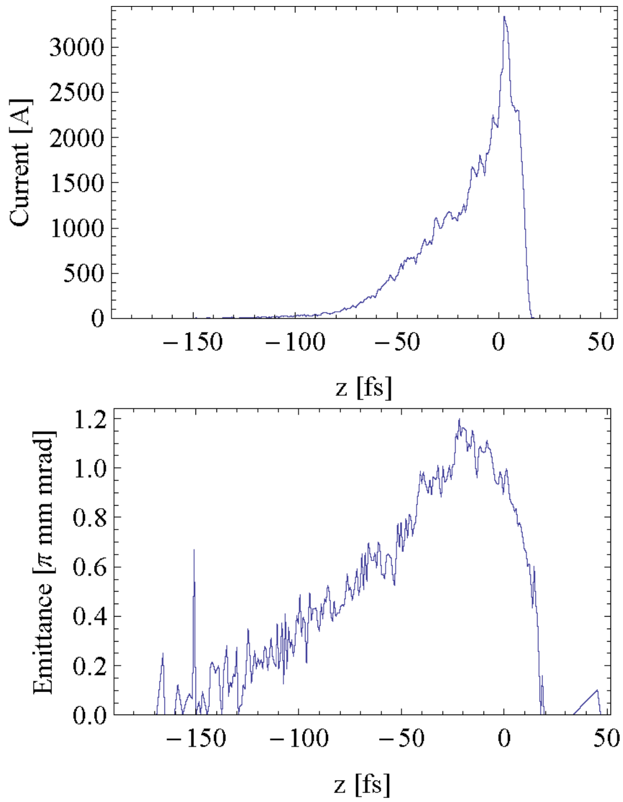

Figure 5: Current and emittance profiles for a highly bunched 100 pC beam at 50 MeV.

JITTER

To investigate the ability of this velocity bunching scheme to operate as an FEL driver, its stability has been investigated. First the beam described above was tracked through two 5 m S-band linac modules after the capture section to reach a final energy of 240 MeV. Then 1000 simulations were carried out with 10,000 macroparticles each, with random jitter applied based on the standard deviations in Table 3 (cut off at three standard deviations). RF jitter was applied individually to each of the five cavities.

Table 3: Jitter Sources

Parameter	Standard deviation	Units
Bunch charge	1	pC
Laser x position	0.02	mm
Laser y position	0.02	mm
Laser arrival time	200	fs
RF gradients	0.1	%
RF phases	0.1	°
Solenoid strengths	0.1	%

Figure 6 summarises the distributions of emittance, bunch length, arrival time and energy when all random jitters are applied. The application of random jitters shows that final beam parameters vary with standard deviations of 18% for projected emittance, 15% for bunch length, 0.32 ps for arrival time and 0.1% for energy.

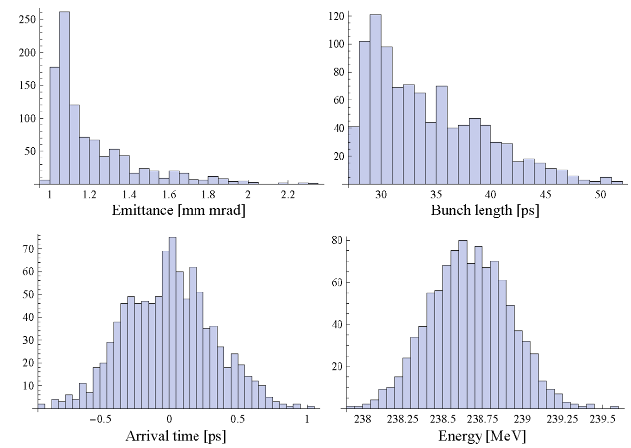

Figure 6: Histograms of beam parameters after 1000 simulations with random jitters applied.

Error Sources

To investigate where this jitter arises, each beam parameter was modified individually. The results are shown in Figure 7. As can be seen, the dominant sources of arrival time instability are the arrival time of the photoinjector laser and the buncher phase and gradient.

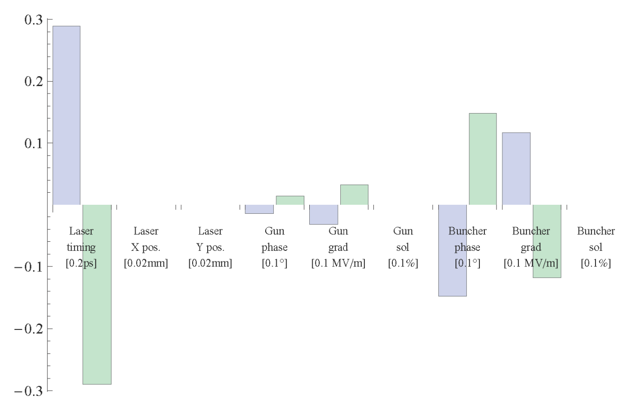

Figure 7: Change in arrival time [ps] from the nominal bunch for a variety of error sources.

SUMMARY

A velocity bunching scheme has been presented based around an S-band RF gun followed by a 2 m long S-band bunching cavity and a further capture cavity. Simulations show that this scheme can compress 100 pC bunches to the sub-100 fs level, kA peak current and 1 mm mrad emittance. Beams with these parameters are capable of driving an FEL, however, jitter will need to be carefully controlled.

REFERENCES

[1] J. Rodier et al., "Construction of the ALPHA-X photo-injector cavity", Proceedings of EPAC 2006.
[2] D. Dowell, "The Limits of Beam Brightness from Photocathode RF Guns", FEL 2010.
[3] K. Deb et al., IEEE Transactions on Evolutionary Computation 6(2), 2002, pp. 183-197.